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AIR-SEA OBSERVED SURFACE TEMPERATURES AND THEIR DISTRIBUTION IN HURRICANES, GULF OF MEXICO

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THESIS

Air-Sea Observed Surface Temperatures
and Their Distribution in Hurricanes,
Gulf of Mexico

by

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by

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ABSTRACT

Observed near-surface air and sea-surface temperatures for three hurricanes -- Hilda (1964), Betsy (1965) and Camille (1969) -- were studied. Composites were made for each of the storms. These composites were oriented to true north, had diameters of 400 n mi and covered the period in the Gulf of Mexico prior to the time the hurricanes reached maximum intensity. The mean air temperature was less than the mean sea-surface temperature, and this difference varied from 1.2C in the outer region of the composites to 2.9C near the center. In the 24-hour period prior to maximum hurricane intensity, the difference was 4.3C near the center. The data also indicated that the distribution of air-sea temperature difference within the hurricanes varied by quadrant with the southeast quadrant containing the largest over-all average difference (2.4C) and the southwest quadrant averaging 1.1C.

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I. INTRODUCTION

A. REVIEW OF THE LITERATURE

Interaction between the atmosphere and the ocean reaches a peak during the hurricane,[1] and by this means the hurricane receives much of its energy from the sea. The surface temperature of the sea must exceed 26C (Palmén, 1948) for hurricane formation. (This temperature is not necessarily a requirement for tropical cyclone maintenance.) According to Riehl (1954), "The ocean is greatly agitated, and large amounts of water are thrown into the air in the form of spray!...Since the surface of contact between air and water increases to many times the horizontal area of the storm, rapid transfer of sensible and latent heat from ocean to air is made possible." The rate of flow of this energy from the sea to the atmosphere is dependent upon the air-sea surface temperature difference. Shuleykin (1970) stated that hurricane modelers have been unable, "...to find the relation between hurricane force and ocean surface temperature which is the most important of all unknown variables."

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[1]In the context of this study, classification of tropical cyclones will be that used in the Glossary of Meteorology, 1959, i.e.: (a) tropical depression, winds up to 34 kt (39 mph); (b) tropical storm, winds of 35 kt (40 mph) to 64 kt (74 mph); (c) hurricane, winds of 65 kt (75 mph) or higher.

A major problem encountered by the meteorologist or oceanographer is getting accurate, synoptic data of sufficient volume which can be applied to his particular area of study. This is particularly so in the case of near-surface and surface observations in the warm-core tropical cyclone, for the obvious reasons implied in Riehl's description above. Malkus (1962) stated, "Through the establishment, in 1955, of the National Hurricane Research Project of the U. S. Weather Bureau and its instrumented aircraft program, more observational information material is available on the interior structure of hurricanes than for any other atmospheric phenomenon." This may be true for upper-air observations; but for near-surface air and sea-surface temperatures, the situation has not improved to any significant extent since Deppermann (1944) stated, "...<u>surface</u> temperature differences can not be appealed to, since they are conspicuously absent."

Most air and sea-surface temperature data are gathered, as would be expected, from surface ship reports. Generally, the number of ships reporting routine six-hourly surface synoptic transmissions appears to have increased significantly (Tisdale and Clapp, 1963). This has not been the case in the near-vicinity of hurricanes, i.e., within two hundred nautical miles of the center, because of the improvement in storm tracking, and the resultant successful evasion of

storm areas by shipping. However, a limited amount of data is being accumulated by unmanned marine buoys.[2]

Authors have employed many procedures to work with the sparse data of the near-surface air and sea-surface temperatures. Working in the hurricane areas of the North Atlantic Ocean, the Caribbean Sea and the Gulf of Mexico, Fisher (1958) found it necessary to draw sea-surface temperature charts on a daily basis. Of the sixteen storms selected for study, Fisher had to discard five because of a paucity of data. Even so, he did not describe the temperature variations within the storms, but only emphasized their surrounding areas. Perlroth (1962) found that lack of data in the immediate vicinity of hurricane Esther (1961) required composited data on a two-to-four-week basis. He also found that working with composites of this length forced much subjectivity into his analyses. Jordan (1964) discovered that the number of sea-surface temperature reports in the vicinity of tropical storms was small and of doubtful accuracy. Jordan (1965) again stated his suspicions of the accuracy

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[2]NOMAD's (Navy Oceanographic Meteorological Automatic Devices) measure five parameters: air temperature, water temperature, barometric pressure, wind speed and wind direction. They have been undergoing testing and evaluation since 1958, and there have been various types and models. Evaluations at various times have included data from the Gulf of Mexico; near Bermuda; off Halifax, Nova Scotia; and off Norfolk, Virginia. Some of the data from the NOMAD buoy situated in the Gulf of Mexico were used in this study. See Fig. 1 for the location of the buoy.

of reported sea-surface temperatures and disagreed with Perlroth's 1962 use of twenty-seven-day composites, and Jordan recommended using some sort of averaging process for compositing periods in excess of a week, by employing means or medians over appropriate areas rather than individual reports. However, Jordan gave no specifics regarding a recommended treatment of such data. Perlroth (1965) also used 10-15-day composites to construct sea-surface temperature patterns in an area from 25N to 35N and from 73W to the east coast of the United States. Thus, it appears that virtually no data have been systematically gathered from the air-sea boundary layer during the life cycle of any hurricane.

Black and Mallinger (1972, unpublished manuscript) used a limited amount of airborne expendable bathythermograph (AXBT), airborne infrared radiometer (ART) data and available ship reports in the region of hurricane Ginger (1971). These data were utilized in construction of daily sea-surface temperature analyses, but the ART data were somewhat suspect due to corrections in sea-surface temperature readings which were required because of variations in the moisture content of the air. To be noted again, however, was the lack of directly observed near-surface air temperature data.

The above mentioned individual studies, for the most part, concerned sea-surface temperatures only. Detailed analyses and reports, other than six-hourly synoptic data, of the surface air temperature in the vicinity of hurricanes

are even more scarce. This shortage of data within the area of the hurricane during its life cycle has made it impossible to describe the actual near-surface atmospheric temperature and sea-surface temperature distributions.

B. OBJECTIVE OF THE STUDY

The objective of the present study is to study the actually observed values of near-surface air and sea-surface temperatures within hurricanes. In particular, the objective is to relate these values to position within the hurricane and to the period of maximum intensity of the storms.

II. APPROACH TO THE PROBLEM

A. GENERAL

Several hurricanes which reached maximum intensity in the Gulf of Mexico were selected. The earlier history of these storms prior to entry into the Gulf was not considered to have any adverse or biasing influence on the data that were gathered in the Gulf for the individual storms. Three hurricanes -- Hilda (1964), Betsy (1965) and Camille (1969) -- were selected. Betsy and Camille were the most destructive hurricanes ever to strike the United States. All of the hurricanes appeared to retain their tropical characteristics throughout the period of the study. They evidently received no additional energy because of influence from extratropical sources, e.g., approaching deepening troughs, surface fronts, etc. This conclusion was based, in part, on Fisher's (1958) statement that, generally, storms south of 35N latitude retain their tropical characteristics.

B. THE SELECTED HURRICANES

1. Hilda (1964)

The circulation that developed into hurricane Hilda formed in an easterly wave just off the southwest coast of Cuba early on 28 September 1964. [Annual Tropical Storm Report - 1964, and Hawkins and Rubsam 1968.] Hilda became a tropical storm while passing over the western tip of Cuba

on 29 September and had become a hurricane by mid-morning on 30 September. Hilda continued moving at a forward speed of about six to eight knots on a northwesterly course, and continued to intensify until about 1800GMT on 1 October, at which time she was located in the central Gulf of Mexico. (See Figs. 1 and 2.) Frank (1964) stated that maximum winds were 130 knots, and the central sea-level pressure was 941 mb.

Even though the only data used for this paper were obtained prior to the time of maximum intensity, it should be noted that Hilda only maintained 130 knot winds for about twelve hours. However, when Hilda crossed the Louisiana coast on the evening of 3 October, maximum surface winds were still in excess of 100 knots.

2. Betsy (1965)

Betsy was indeed a unique hurricane. In fact, she was one of the great hurricanes of the twentieth century, and the most devastating to have occurred through the year 1965, with structural damage exceeding $1.4 billion. [Clark, 1966.] Betsy's intensity and track across the northern part of the Gulf are also shown in Figs. 1 and 2. Before arrival in the Gulf of Mexico on the morning of 8 September, Betsy had been a hurricane since mid-day on 30 August. The maximum wind speed prior to Betsy's arrival in the Gulf was about 118 knots on the morning of 4 September. Betsy's wind

speed, when she entered the Gulf, was about 110 knots with gusts to 128 knots reported. After passing south of Florida, Betsy turned toward the northwest and increased forward speed to about 19 knots, which is well above the average speed for storms in the Gulf.

Following a slight decrease in wind speed shortly after entry into the Gulf, Betsy steadily increased in intensity until maximum surface winds of about 130 knots, and minimum observed sea-level pressure of 941 mb occurred at about 0000GMT on 10 September. [Annual Tropical Storm Report - 1965.] Three hours later Betsy made landfall at Grand Isle, Louisiana, and underwent steady, rapid decay after that time.

3. Camille (1969)

The initial disturbance that eventually became hurricane Camille was first detected as an inverted "V" in satellite pictures on 5 August 1969 just west of Dakar, Senegal. Little did anyone suspect at the time that Camille would ultimately become "...the most destructive, if not the most intense, in the history of Atlantic hurricanes..." (Simpson, Sugg and Staff, 1970) and cause damage exceeding the $1.4 billion attributed to hurricane Betsy in 1965.

Camille was subsequently tracked westward and reached hurricane intensity late on 14 August approximately 200 n mi south of the western tip of Cuba. Camille continued steady

intensification while on a northwesterly course at a speed of about ten knots, except for a slight decrease in intensity and speed of movement as she passed over the western tip of Cuba. Camille's track and intensity are shown in Figs. 1 and 2.

Once over the warm Gulf of Mexico waters again, intensification continued as Camille moved on her north-northwest journey until about 1815GMT on 17 August when, "...an Air Force plane reported a central pressure of 905 mb with an estimated 165 knots of wind. This pressure was the second lowest on record in the United States, with the lowest occurring in the Labor Day Hurricane of 1935." [Annual Hurricane Summary - 1969.] This intensity was maintained until Camille went ashore at about 0300GMT on 18 August just east of Bay St. Louis, Mississippi. Thereafter, Camille underwent rapid decay.

C. ACCURACY OF THE DATA

There are many evaluations of the accuracy of ship reported observational data, particularly of sea-surface temperature. Franceschini (1955) found merchant ship reports comparable with data gathered by oceanographic surveys of sea-surface temperature in the Gulf of Mexico. Fisher (1958) found it necessary to discard only, "...a few percent of the total data." Tisdale and Clapp (1963), on the other hand, mentioned, "...the general poor quality of ship observations..."

of air and sea-surface data. Wolff, Carstensen and Laevastu (1967) compared sea-surface temperatures obtained by the bucket method and temperatures obtained at ship injection intakes and stated: "Numerous studies exist on the accuracy, sources of errors and differences of these two methods. However, the gross comparisons of the results of these studies indicates, despite some contrary claims, that the methods are about equal."

Ship reported synoptic sea-surface data are taken from injection temperature readings, and for the most part, come from merchant ships. Injection intakes are located approximately three to seven meters below the surface. Thus, some deviations from actual sea-surface temperatures are probably present in the data. The NOMAD water temperature sensor was located approximately one-half meter below the surface, and should, therefore, prove to be a more accurate source of sea-surface temperatures.

Air temperature has traditionally not been as suspect as sea-surface temperature. This should not be taken to mean, however, that this data should not also be carefully scrutinized. In hurricane situations the difficulty of making accurate observations is, of course, compounded.

D. SOURCES OF THE DATA

The ship reports, aircraft reports and NOMAD information used in this study came from several sources. Two primary

sources were Fleet Numerical Weather Central (FNWC), Monterey, California, and the "Historical Weather Map Series" which was obtained from the Environmental Prediction Research Facility (EPRF), Monterey, California. Two other sources which contained important information were the 'Selected Gale Observations North Atlantic' section of "Mariner's Weather Log" and NOMAD data from a National Oceanographic Data Center (NODC) publication by Marcus and Smith (1966). The "best track"[3] and wind speed, i.e., intensity data were taken from the Annual Hurricane Summaries which are published annually by U. S. Fleet Weather Facility, Jacksonville, Florida.

From the time work was first begun on this study, it was evident that gathering data would be a major problem. It was anticipated that little data would be found. This anticipation was soon proved to be correct. For the 34 reporting periods, only 235 six-hourly reports were available for the three hurricanes. This total of ship reports was prior to elimination of erroneous reports. An additional 268 reports were extracted from the "Historical Weather Map Series." However, some of this data represented duplicated information. Any data which contained gross errors, i.e.,

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[3]The "best track" is determined by post analysis and is based on all available position data concerning the tropical cyclone, e.g., reconnaissance aircraft fixes, land station radar fixes, satellite pictures, special aircraft and ship reports plus surface and upper-air analyses.

position coordinates were incorrect, the magnitude of the air or water temperature was unrealistic, etc, were considered erroneous. Only five of 24 reports from the "Mariner's Weather Log" were ultimately included in this study. The NOMAD data derived from NODC publications proved to be very valuable. However, for some reason, a large portion of the data periods presented in the "Historical Weather Map Series" showed NOMAD data missing. It was possible to obtain this information from Marcus and Smith (1966). About 20 very important reports were obtained in this manner, including all of the data contained in Fig. 21.

The above sources totaled 547 reports of position and temperature prior to being analyzed for possible duplication, errors or other reasons for being eliminated from the study. Only 253 air temperatures and 240 sea-surface temperatures were finally selected for use.

E. ORGANIZATION OF THE DATA

As stated in the previous section, the most striking aspect of the data was its scarcity. Each of the 34 six-hourly reporting periods had a mean of about sixteen ship reports. The 1800GMT reports were the most numerous in practically every instance. This was probably because this hour corresponded to that "local" time in the Gulf of Mexico which occurred during the "normal" work day of the ship's radio operators. In other words, it appears very few reports

are transmitted if the radio operator must be paid overtime when doing so. Of the 16 ship reports for each six-hourly period, a mean of about seven reports contained information suitable for use in the final analysis.

After the data had been gathered, it was reduced to a common format. All of the reports for each six-hour period were plotted on separate maps of the area of interest. Those reports which had appeared in more than one source and those reports deemed erroneous were now discarded.

The six-hour "best track" positions were next plotted on the 34 above mentioned maps. Data within a two hundred n mi radius of the center of the hurricanes were selected if it appeared that these data were not in error. Then, using the hurricane center as a reference, the azimuth in degrees from north, and the radial distance, were determined for each observation.

Separate composites[4], each of which was oriented to true north, were constructed for the air and sea-surface temperatures of each hurricane. This resulted in a total of six composites of data within 200 n mi of the hurricane centers. Data were plotted on the composites throughout

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[4]In composites, as used in this study, all data associated with a particular hurricane, were plotted using the hurricane center as a reference and plotted as if the hurricane center had remained at a single position and all observations had been made at one time.

the duration of the hurricanes in the Gulf of Mexico, and the time involved thus was different for each hurricane. Data for Hilda were composited from the time she developed into a tropical depression at about 1800GMT on 28 September until maximum intensity occurred at about 1800GMT on 1 October -- a period of about three days encompassing 13 reporting periods. Betsy's composites, on the other hand, covered the period of time between entry into the Gulf as a full-blown hurricane at about 0000GMT on 8 September until maximum intensity was reached two days later at about 0000GMT on 10 September. This resulted in a total of nine reporting periods. Camille's composites extended from about 0000GMT on 15 August until her maximum intensity occurred at about 1800GMT on 17 August 1969 -- a period of almost three days and 12 reporting periods. The hurricane composites are shown in Figs. 3 - 8.

III. TEMPERATURE DISTRIBUTION BY RADIAL BANDS

A. GENERAL

To illustrate surface temperature and air-sea difference variations toward the storm center, the average radial band values in Figs. 9 and 10 were plotted at the mid-points of the bands.

B. HILDA

As mentioned in the previous chapter, two composites were constructed for each hurricane -- one for the air temperature and the other for the sea-surface temperature. The air temperature and the sea-surface temperature composites for hurricane Hilda are shown in Figs. 3 and 4. Both covered the 13 reporting periods between 1800GMT on 28 September and 1800GMT on 1 October. Data for the individual 50 n mi bands, including the difference between the air and sea-surface temperature, are tabulated in Table I. Some of these data were also used in the construction of Figs. 9 and 10.

The mean value of the sea-surface temperature (Fig. 9) increased 0.9C as the center of Hilda was approached from the outermost band. The mean air temperature, on the other hand, decreased from 28.0C to 27.0C as the center was approached. These results may be compared to changes which would be caused by the thermodynamic processes involved.

A sea-level pressure of 1000 mb was assumed to exist at the outer edge of the hurricane, and the pressure was first reduced along a dry adiabat to the lowest observed sea-level pressure of Hilda (941 mb). This dry adiabatic expansion would have resulted in a temperature drop to about 23.0C, a decrease of about 5.0C, which was much larger than the 1.0C decrease observed. If the same sea-level pressure of 1000 mb were assumed for the outer area of the storm, and this pressure were then reduced to 941 mb along a saturated adiabat, the temperature would have dropped to about 26.0C, a decrease of about 2.0C. This 2.0C decrease was only 1.0C greater than obtained from the observed data, but it is very doubtful that conditions are actually saturated within this area of a hurricane. Assuming a more realistic value (e.g. 85%) for the relative humidity in the outer area of the hurricane, and following the dry adiabatic lapse rate from 28.0C at 1000 mb results in saturated conditions at about 970 mb. Then saturated expansion from 970 mb to approximately 941 mb would result in a temperature of about 24.5C, which was about 2.5C less than the mean value observed in the inner area of Hilda.

Thus, it appeared that these assumed processes were inconsistent with the observations described here and with Byer's (1944) conclusion that the spiraling flow of air toward the center was esentially isothermal for the hurricane.

This meant that the air must have acquired sensible heat during its travel toward the lower pressure of the center. As Riehl (1954) stated: "That tropical storms contain a local heat source within their circulation will greatly facilitate the explanation of the temperature distribution aloft and of the surface barograms."

Figure 10 showed that the difference in the air and sea-surface temperatures also increased from a value of 0.9C in the outer band to 2.8C in the inner band.

C. BETSY

The air temperature and the sea-surface temperature composites for hurricane Betsy are shown in Figs. 5 and 6. Both composites contain reported data for the nine periods between 0000GMT on 8 September and 0000GMT on 10 September 1965. The data for the 50 n mi radial bands, plus the difference between air and sea-surface temperatures, are contained in Table II. Some of these data were also used in the construction of Figs. 9 and 10.

The sea-surface temperature near Betsy, as indicated in Fig. 9, remained essentially constant from the outer band to the next band, but dropped about 0.7C between the 50 and 100 n mi bands. Then an increase of about 0.9C to a value 0.3C higher than the temperature at the outer band was noted. The air temperature steadily decreased from 27.6C to 25.6C toward the center. Assumptions of the type made for Hilda

above were also made for Betsy, i.e., the sea-level pressure in the outer area of the hurricane was assumed to be 1000 mb and the relative humidity about 85% in the lowest layer of the storm. Dry adiabatic expansion to saturation at about 970 mb, and saturated expansion to the observed sea-level pressure of 941 mb would have resulted in a temperature of about 23.7C, which would be about 1.9C less than the mean of the observed data, 25.6C, near the center of the hurricane. Thus, there was also a requirement for sensible heat transfer to explain the essentially isothermal expansion for Betsy. The air and sea-surface temperature difference (Fig. 10) increased from a value of 1.0C in the outer band to a value of 1.7C in the adjacent band, with a slight decrease to 1.6C in the next band. This value was followed by an increase to 3.3C in the inner band.

D. CAMILLE

The air temperature composite for hurricane Camille is depicted in Fig. 7 and the sea-surface temperature is given in Fig. 8. These composites contained data for the 12 reporting periods between 0000GMT on 15 August and 1800GMT on 17 August 1969. The data for the 50 n mi bands, plus the air-sea temperature differences, are contained in Table III. Some of these data were also further used in the construction of Figs. 9 and 10.

The mean of the sea-surface temperature (Fig. 9) decreased slightly from the outside band to the 50-to-100 n mi band, and then increased as the center was approached. However, the temperature of the inner band was about 0.2C less than that of the outer band. It was also noted that Camille contained the highest sea-surface temperatures, but the representativeness of this data was open to question, because only two observations were available near the center. The air temperature decreased slightly toward the center, with a total drop of 1.3C from 28.3C to 27.0C. If the same assumption of outer-area sea-level pressure of 1000 mb, observed air temperature of 28.3C, and a relative humidity of about 85% in the lowest layer of the hurricane are applied, dry adiabatic expansion to saturation at about 970 mb and saturated expansion to the observed, central sea-level pressure of 905 mb would produce a temperature of about 23.2C, which was about 3.8C less than the mean of the observed temperature, 27.0C, near the center of Camille. As was the case for hurricanes Hilda and Betsy, the sensible heating explanation with essentially isothermal expansion appeared to be consistent for Camille. The difference between the air and sea-surface temperatures (Fig. 10) decreased from 1.9C at the outer band to a value of 1.3C in the adjacent band. Thereafter, the temperature difference increased steadily until a value of 3.0C was reached in the inner band.

E. THE COMBINED HURRICANES

After the data for the individual hurricanes had been studied, all of the data were combined (Table IV) for the 50 n mi bands, including the differences between air and sea-surface temperatures.

As shown by Fig. 9, the mean value of the combined sea-surface temperatures decreased slightly from the outer band to the 50-to-100 n mi band. The sea-surface temperature increased to a value at the inner band that was about 0.4C greater than the temperature at the outer band. The air temperature decreased by 1.3C as the center was approached. Figure 10 showed that the difference between the air and sea-surface temperatures for the combined hurricane data increased as the center was approached. This increase was from a value of 1.2C in the outer band to 2.9C in the inner band, with 1.1C of this change occurring between the inner two bands.

IV. TEMPERATURE DISTRIBUTION BY QUADRANTS

A. GENERAL

Another method of analyzing the data consisted of dividing into quadrants the composited information for each of the hurricanes. The orientation of the quartering lines in the tabulated data shown in Figs. 11 - 14 was north-south and east-west. It was felt that this might serve to provide another insight into the air and sea-surface temperature distributions within the hurricanes.

In one-half of the sets of data for each quadrant, it was apparent that different numbers of observations were presented for the air and water temperature reports. In practically every instance, this difference was because of missing data. There were a few occasions, however, when this difference resulted from erroneous data having been discarded.

To be kept in mind also was the fact that Hilda and Camille crossed the Gulf on tracks that generally ran from south to north. Betsy entered the Gulf just south of Florida and followed a westerly and then northwesterly track.

The quadrant data were also displayed in line diagrams, as can be seen in Figs. 15 and 16. No distribution of the mean temperatures within the quadrants was implied here, because this information was shown in Figs. 3 - 8.

B. HILDA

The observed air and sea-surface data, by quadrant, in hurricane Hilda are shown in Figs. 11 and 15. The surface air temperature was less in all quadrants than the water temperature, and the magnitude of this difference varied from quadrant to quadrant. The air temperature was lowest, 27.1C, in the southeast quadrant and highest, 28.7C in the southwest quadrant. The water temperature, on the other hand, was lowest, 28.9C in the northeast quadrant and highest, 29.7C, in the southwest quadrant. The difference of the means of the air and water temperatures was smallest, 1.0C, in the southwest quadrant and largest, 2.3C, in the southeast quadrant, as can be seen in Figs. 11 and 16.

C. BETSY

The observed air and sea-surface data, by quadrants, in hurricane Betsy are shown in Figs. 12 and 15. As was the case for Hilda, the mean air temperature was less in all quadrants than the water temperature, and the magnitude of this difference varied from quadrant to quadrant. The air temperature was lowest, 26.0C, in the northeast quadrant and highest, 27.3C, in the southwest quadrant. The water temperature was lowest, 27.0C, in the northeast quadrant and highest, 28.8C, in the southeast quadrant. The difference between the means of the air and water temperatures, as shown in Fig. 16, was smallest, 0.9C, in the northwest

quadrant, and, as was the case for the Hilda data, the difference was largest, 1.7C, in the southeast quadrant. (The unusually small number of observations in the northern half of Betsy, particularly the three data points in the northeast quadrant, served to cast doubt on the representativeness of these averages.)

D. CAMILLE

The observed air and sea-surface data, by quadrant, in hurricane Camille are as shown in Figs. 13 and 15. As was the case in Hilda and Betsy, the mean air temperature was less in all quadrants than the water temperature, and the magnitude of the difference was different in each of the quadrants. The air temperature was lowest, 27.0C, in the southeast and highest, 28.4C, in the southwest quadrant. The water temperature, on the other hand, was lowest, 29.6C, in the northeast quadrant and highest, 29.8C, in the southeast quadrant. The differences between the means of the air and water temperatures, as shown in Fig. 16, was smallest, 1.3C, in the southwest quadrant, and, as was the case in the Hilda and Betsy data, was largest, 2.8C, in the southeast quadrant. (Having only five observations in the northeast quadrant also served to cast doubt on the representativeness of these data.)

E. THE COMBINED HURRICANES

The observed air and sea-surface data for the combined hurricanes, by quadrant, are shown in Figs. 14 and 15. The mean of the combined air temperatures was found to be lowest, 27.0C, in the southeast quadrant and highest, 28.1C, in the southwest quadrant. For each of the three hurricanes, the southwest quadrant contained the highest air temperatures. The mean of the combined water temperatures was found to be lowest, 28.8C, in the northeast quadrant and highest, 29.4C, in the southeast quadrant. The magnitude of the difference between the combined means of the air and water temperatures was smallest, 1.1C, in the southwest quadrant and largest, 2.4C, in the southeast quadrant.

V. HURRICANE INTENSIFICATION

A. GENERAL

As mentioned earlier, the rate of flow of energy from the sea to the atmosphere is dependent upon the air-sea temperature difference. Thus, it would appear that this rate of flow of energy, and the resultant intensification of the hurricane, might be indicated by the magnitude of this temperature difference. It seemed reasonable to expect that maximum intensification should occur during the period of time when the magnitude of the air and sea-surface temperature difference was greatest.

Thus, an attempt was made to look at the storms for shorter time periods preceding maximum intensity, rather than compositing thoroughout the life cycle in the Gulf, as was done in previous chapters. The time periods chosen were: (1) 24-48 hours prior to maximum intensity and (2) 24 hours prior to maximum intensity.

B. 24-TO-48 HOURS PRIOR TO MAXIMUM INTENSITY

The mean air and sea-surface temperature data for the individual 50 n mi bands of the combined hurricanes for the period of time between 24 and 48 hours prior to maximum intensity are shown in Table V. The data within 50 n mi of the center were practically non-existent, with only two observations. The magnitude of the air-sea temperature

differences increased from 1.3C at the outer band to 2.8C at the inner band -- a net increase of 1.5C.

The total of 103 air temperature observations had a mean of 27.4C and the 98 sea-surface temperature observations had a mean of 29.0C. This gave 1.6C as the magnitude of the difference between air and sea-surface temperatures. These results were 0.2C greater than the mean sea-surface temperature of 29.1C, the mean air temperature of 27.7C and their mean difference, 1.4C, given in Table IV.

C. 24 HOURS PRIOR TO MAXIMUM INTENSITY

The mean air and sea-surface temperature data for the individual 50 n mi bands of the combined hurricanes for the period 24 hours prior to maximum intensity are as shown in Table VI. Even though there were only six observations in the innermost band, more confidence was placed in this data than in the data for the same band in the 24-to-48 hour period prior to maximum intensity. The magnitude of the temperature differences increased toward the center from 1.2C at the outer band to 4.3C at the inner band -- a net increase of 3.1C.

The total of 102 air temperature observations had a mean of 27.5C, and the 96 sea-surface temperature observations had a mean of 29.3C. This gave 1.8C as the magnitude of the difference between the air and sea-surface temperatures. This 1.8C was 0.2C greater than the 1.6C difference between

the mean of the air and sea-surface temperatures for the 24-to-48-hour period prior to maximum intensity and 0.4C greater than the 1.4C difference between the means of air and sea-surface temperatures for the duration of the storms in the Gulf.

Figures 19 and 20 provide a picture of what occurred during the 24-hour period immediately prior to maximum intensity, and should be compared to Figs. 9 and 10 which dealt with the life-cycle of the hurricanes while in the Gulf. The same general statements regarding the radial band information of Section A of Chapter III also applied in Figs. 19 and 20. There were slight variations in the mean sea-surface temperatures of the individual storms, but the net change for the combined hurricanes was an increase of only 0.3C as the center was approached from the outer band (Fig. 19). The mean air temperature for the combined hurricanes during the same period decreased steadily in proceeding toward the center from the outer band. The net change was a decrease of 2.8C.

The air and sea-surface temperature differences for each of the radial bands for the individual hurricanes as well as the combined data were plotted in Fig. 20. In the case of each hurricane and the combined data, the temperature differences increased steadily toward the center from the outer band. The combined data, which encompassed the period

24 hours prior to maximum intensity showed the temperature differences increased from a value of 1.2C at the outer band to a value of 4.3C at the inner band. This was a net increase of 3.1C, and 1.8C of this increase took place between the inner two bands.

These temperatures were compared with Fig. 10, which showed the difference between the air and sea-surface temperatures for the combined hurricane data for the entire period of time the hurricanes spent in the Gulf. The following relationships were noted: (1) the magnitude of the mean air-sea temperature difference was the same, 1.2C, for the outer band in both cases; (2) the magnitude of the mean air-sea temperature differences was greater, 4.3C, for the 24-hour period as compared to 2.9C for the longer period; (3) the net increase in temperature difference was 3.1C for the 24-hour period as compared with 1.7C for the longer period. Thus, it was seen that the magnitude of the differences between the air and sea-surface temperatures was larger in the 24-hour period prior to the occurrence of maximum intensity, when these differences were compared to the longer periods of time in Chapter III.

VI. HURRICANE HILDA AND THE GULF OF MEXICO NOMAD

A. GENERAL

Prior to this time in the study, the observed data were treated as if the hurricanes had remained in one position, and the observations had been moved. One case was found in which the data were obtained in a different manner. This instance resulted when hurricane Hilda passed within about 40 n mi of the Gulf of Mexico NOMAD. The data from this passage were analyzed and compared with the radial band information obtained in earlier chapters.

B. DISCUSSION OF THE PASSAGE

Figure 1 shows the track of hurricane Hilda relative to the Gulf of Mexico NOMAD, which was anchored in 1875 fathoms of water at 25N and 90W. NOMAD was powered by a SNAP-7D nuclear-isotope powered battery charger programmed to re-cycle every three hours. The closest point of approach of Hilda's center was approximately 40 n mi to the southwest of NOMAD, and this occurred a short time before 1200GMT on 1 October. Marcus and Smith (1966) stated that during the passage of Hilda, "...all the parameters combined to show a perfectly reasonable model of a hurricane passage."

A plot of air and water temperatures versus time is shown in Fig. 21. The air temperature report at 0600GMT on 30 September appeared to be erratic, but this was

difficult to explain since the reports before and after this time appeared good. This marked increase in temperature may have been associated with subsidence which could have been occurring in the outer region of the hurricane (Hilda was approximately 190 n mi to the southeast of NOMAD at this time) or the increase could have been associated with subsidence in the region of a rainband. (Perhaps further research will uncover some previously unknown phenomenon associated with hurricane rainbands.) Beginning at about 18000GMT on 30 September, the air temperature dropped steadily for 18 hours. (This drop was possibly associated with the hurricane rain.) As the hurricane approached, there were only minor fluctuations in water temperature until about 1200GMT on 1 October. At this time the temperature of the water began to decrease steadily. This was probably caused by a combination of effects, namely: (1) the loss of heat from the water to the atmosphere with resultant convective overturning; (2) mechanical mixing by the wind; and (3) upwelling -- though the decrease was not as large as would be expected for water upwelled in this part of the Gulf of Mexico. Also, to a minor extent, the surface water was probably cooled by the colder water of the falling precipitation.

However, the most interesting aspect of this graph was as Hilda was approaching from the southeast. In the period

of time prior to about 1800GMT on 30 September, the temperature difference between air and water was small and variable. By 1800GMT Hilda had approached to within approximately 100 n mi of NOMAD, and the temperature difference between the air and water was approximately 1.2C. As Hilda came nearer to the buoy, the difference between the air and water temperatures increased markedly! By 0000GMT on 1 October Hilda had closed the buoy to about 70 n mi, and the temperature difference was now approximately 2.8C. Six hours later Hilda was about 50 n mi from NOMAD, and the temperature difference was now approximately 4.4C. The closest point of approach of Hilda to the buoy occurred just before 1200GMT on 1 October, and the difference between the air and water temperatures had increased to a maximum value of about 5.6C. This temperature difference began to decrease as Hilda began to move away from NOMAD and was down to approximately 3.3C at 1800GMT.

This occurrence was consistent with the results obtained in Chapter III, in that nearer the center of the hurricane the magnitude of the difference between the air and sea-surface temperatures increased. However, the magnitude of the air and water temperature differences when Hilda passed NOMAD were larger than the magnitude shown in Fig. 10. It should be kept in mind that in this 24-hour period, while the maximum difference between air and sea-surface temperature took place, Hilda was undergoing maximum intensification.

Figure 20 showed differences in magnitude between air and water temperatures in the 24 hours prior to maximum intensity, which compared very favorably with the results obtained from the above NOMAD data. The decrease in difference between air and water temperature at 1800GMT may have occurred as the result of several effects. The rate of response of a hurricane to its driving mechanisms is not known. However, it was entirely possible that the large, 5.6C, air and water temperature difference at 1200GMT initiated the buildup to maximum intensity at that time. Inspection of Fig. 2 showed that the duration of Hilda's maximum intensity was very short, with intensity decreasing soon after the maximum was reached. Also, Hilda began to increase the distance between her and the buoy at about 1200GMT.

Comparing the Hilda - NOMAD data with the quadrant information obtained for the hurricanes in Chapter IV gave inconclusive results. The buoy was located in the northwest quadrant of the hurricane until 0600GMT and was in the northeast quadrant until the time of maximum intensity. Mean temperature differences in the northwest quadrant from the ship observations (Fig. 18) were very small, about 0.9C, in the 24-hour period prior to maximum intensity. This did not compare with the large air-water temperature difference at 1200GMT. After 1200GMT when the buoy was well into the

northeast quadrant, the mean temperature differences for all the hurricanes was larger, about 1.8C, but certainly not of the magnitude indicated by the NOMAD data.

.Important questions to be asked here are: "Did the increase in the temperature difference occur because of the approach of the hurricane? Did the increase in the temperature difference occur because the hurricane was increasing in intensity as it approached? Was this phenomenon attributable to a combination of the above factors?"

It was felt that the last possibility was the most probable explanation, i.e., the approach of the hurricane caused the temperature difference to increase somewhat. Then the relatively large magnitude of the temperature difference, when compared to the differences of the mean temperatures of the entire hurricane, resulted in maximum intensity occurring at this time.

VII. CONCLUSIONS

1. There is a difference in the air-sea surface temperatures within a hurricane -- as indicated by these data for the three hurricanes studied -- and the magnitude of this average difference increases from about 1C at a radial distance of about 200 n mi to about 3C near the center of the hurricane.

2. The magnitude of the air-sea temperature difference was apparently largest in the 24-hour period prior to the occurrence of maximum intensity. This difference increased from about 1C to about 4C between 200 n mi and the center of these hurricanes.

3. The distribution of the air-sea temperature differences within these hurricanes, as indicated by observations, is not symmetrical, but the value is different in each quadrant with the largest difference appearing in the southeast quadrant.

VIII. RECOMMENDATIONS

1. The most important recommendation to be made is that further studies with particular emphasis on the observed distribution of moisture within the hurricane must be conducted.

2. Additional deep sea buoys, such as NOMAD, should be placed in the Caribbean Sea, the Gulf of Mexico and off the east coast of the United States.

3. Better temperature sensing devices should be placed aboard all ships, and these devices should be used.

4. A systematic plan of attack should be formulated and executed to fill the environmental data gap that exists in the boundary layer of hurricanes.

5. The expendable bathythermograph (XBT) should be placed aboard all United States sea-going vessels, military and civilian.

RADIAL BAND (n mi)	AIR TEMPERATURE (°C)	SEA-SURFACE TEMPERATURE (°C)	DIFF. OF MEANS
0 to 50	27.0/23.9-31.1/ 7	29.8/28.4-30.6/ 6	2.8
50 to 100	27.2/23.9-30.0/ 17	29.2/27.2-32.2/ 17	2.0
100 to 150	27.5/23.9-31.1/ 53	29.2/27.8-31.1/ 49	1.7
150 to 200	28.0/26.1-30.0/ 46	28.9/25.0-32.2/ 43	0.9
TOTALS	27.6/23.9-31.1/123	29.1/25.0-32.2/115	1.5

Table I. Mean Radial Band Data for Hurricane Hilda for the Period 281800GMT SEP - 011800GMT OCT 1964. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

RADIAL BAND (n mi)	AIR TEMPERATURE (°C)	SEA-SURFACE TEMPERATURE (°C)	DIFF. OF MEANS
0 to 50	25.6/25.0-26.1/ 2	28.9/ 28.9 / 2	3.3
50 to 100	26.4/25.0-28.3/ 11	28.0/26.1-29.4/ 11	1.6
100 to 150	27.0/25.0-28.3/ 12	28.7/26.7-30.0/ 12	1.7
150 to 200	27.6/25.6-30.0/ 23	28.6/26.1-30.0/ 23	1.0
TOTALS	27.2/25.0-30.0/ 48	28.5/26.1-30.0/ 48	1.3

Table II. Mean Radial Band Data for Hurricane Betsy for the Period 080000GMT SEP - 100000GMT SEP 1965. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

RADIAL BAND (n mi)	AIR TEMPERATURE ($^{\circ}$C)	SEA-SURFACE TEMPERATURE ($^{\circ}$C)	DIFF. OF MEANS
0 to 50	27.0/26.1-27.8/ 2	30.0/ 30.0 / 2	3.0
50 to 100	27.0/25.0-28.9/ 14	29.2/26.1-31.7/ 15	2.2
100 to 150	28.0/26.1-30.0/ 28	29.3/27.2-31.7/ 26	1.3
150 to 200	28.3/25.0-31.1/ 38	30.2/28.3-31.1/ 34	1.9
TOTALS	28.0/25.0-31.1/ 82	29.7/26.1-31.7/ 77	1.7

Table III. Mean Radial Band Data for Hurricane Camille for the Period 150000GMT AUG - 171800GMT AUG 1969. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

RADIAL BAND (n mi)	AIR TEMPERATURE ($^{\circ}$C)	SEA-SURFACE TEMPERATURE ($^{\circ}$C)	DIFF. OF MEANS
0 to 50	26.8/23.9-31.1/ 11	29.7/28.9-30.6/ 10	2.9
50 to 100	27.1/23.9-30.0/ 42	28.9/26.1-32.2/ 43	1.8
100 to 150	27.6/23.9-31.1/ 93	29.2/27.8-31.7/ 87	1.6
150 to 200	28.1/25.0-31.1/107	29.3/25.0-32.2/100	1.2
TOTALS	27.7/23.9-31.1/253	29.1/25.0-32.2/240	1.4

Table IV. Mean Radial Band Data for the Combined Hurricanes for the Periods of Time Given in Tables I, II, III. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

RADIAL BAND (n mi)	AIR TEMPERATURE (^oC)	SEA-SURFACE TEMPERATURE (^oC)	DIFF. OF MEANS
0 to 50	26.9/25.6-28.3/ 2	29.7/29.4-30.0/ 2	2.8
50 to 100	27.0/25.0-30.0/ 18	28.8/26.1-32.2/ 18	1.8
100 to 150	27.3/22.2-31.1/ 41	29.0/25.0-31.7/ 38	1.7
150 to 200	27.7/25.6-30.0/ 42	29.0/25.0-30.6/ 40	1.3
TOTALS	27.4/22.2-31.1/103	29.0/25.0-32.2/ 98	1.6

Table V. Mean Radial Band Data for the Combined Hurricanes for the 24-to-48-hour Period Prior to Maximum Intensity.
(MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

RADIAL BAND (n mi)	AIR TEMPERATURE (^oC)	SEA-SURFACE TEMPERATURE (^oC)	DIFF. OF MEANS
0 to 50	25.3/23.9-26.1/ 6	29.6/28.9-30.6/ 6	4.3
50 to 100	26.9/23.9-28.9/ 16	29.4/27.2-31.7/ 16	2.5
100 to 150	27.7/25.6-29.4/ 33	29.4/27.2-31.1/ 31	1.7
150 to 200	28.1/25.0-31.1/ 47	29.3/25.6-32.2/ 43	1.2
TOTALS	27.5/23.9-31.1/102	29.3/25.6-32.2/ 96	1.8

Table VI. Mean Radial Band Data for the Combined Hurricanes for the 24-hour Period Prior to Maximum Intensity.
(MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

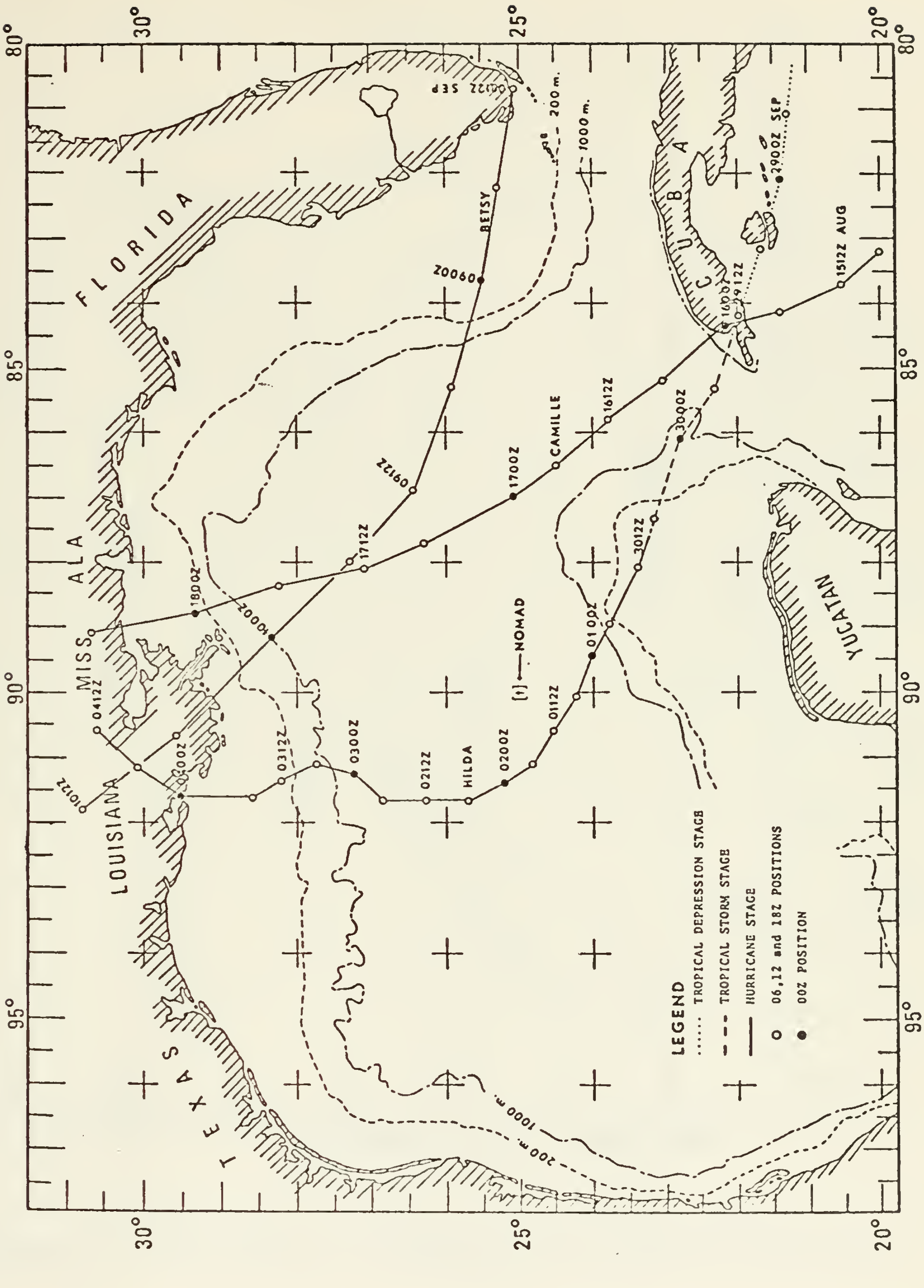

Figure 1. Tracks of the selected hurricanes and the location of the NOMAD Buoy.

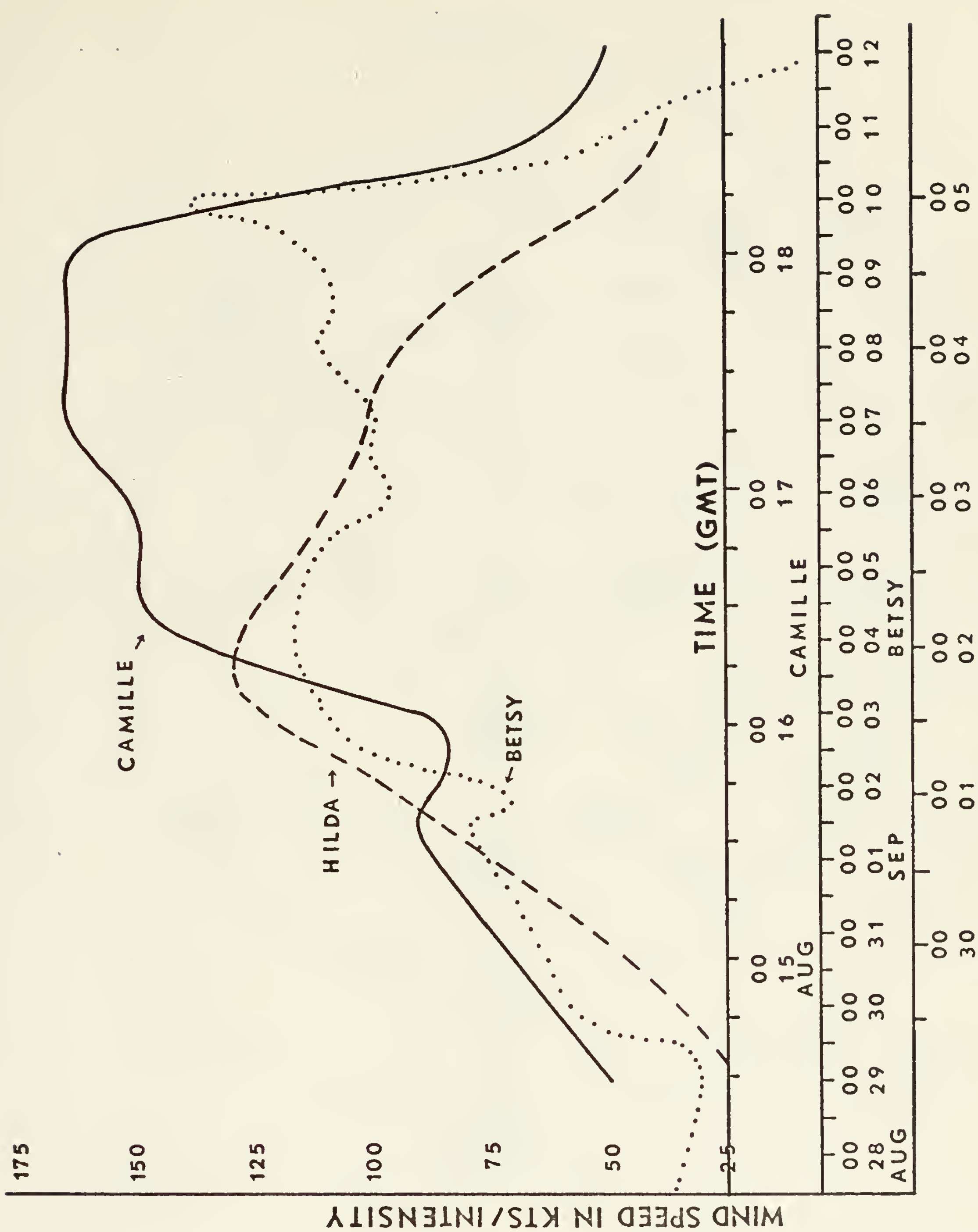

Figure 2. Intensity vs. Time for the Selected Hurricanes.

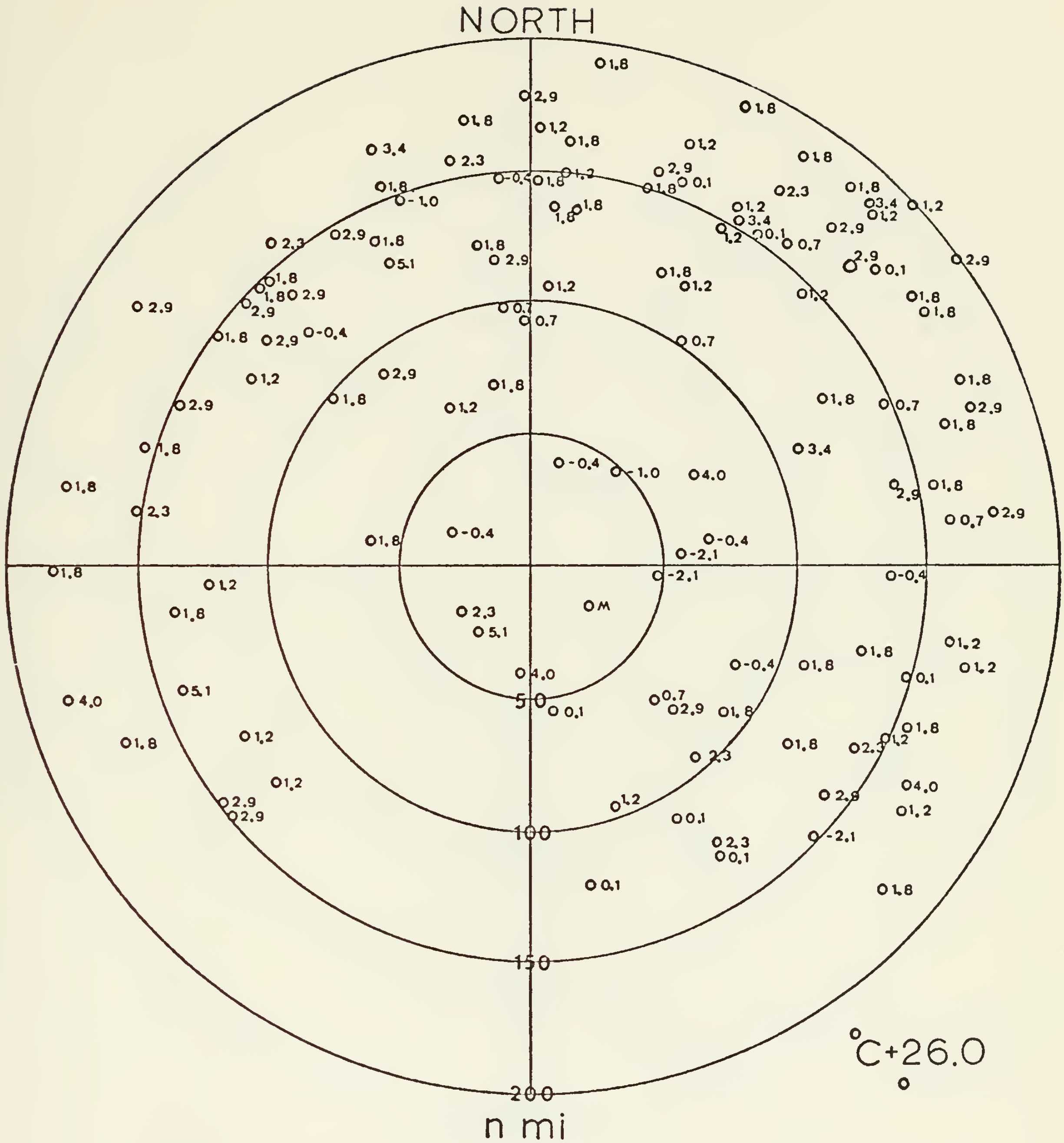

Figure 3. Composite of Observed Air Temperatures for Hurricane Hilda -- 281800GMT SEP - 011800GMT OCT 1964.

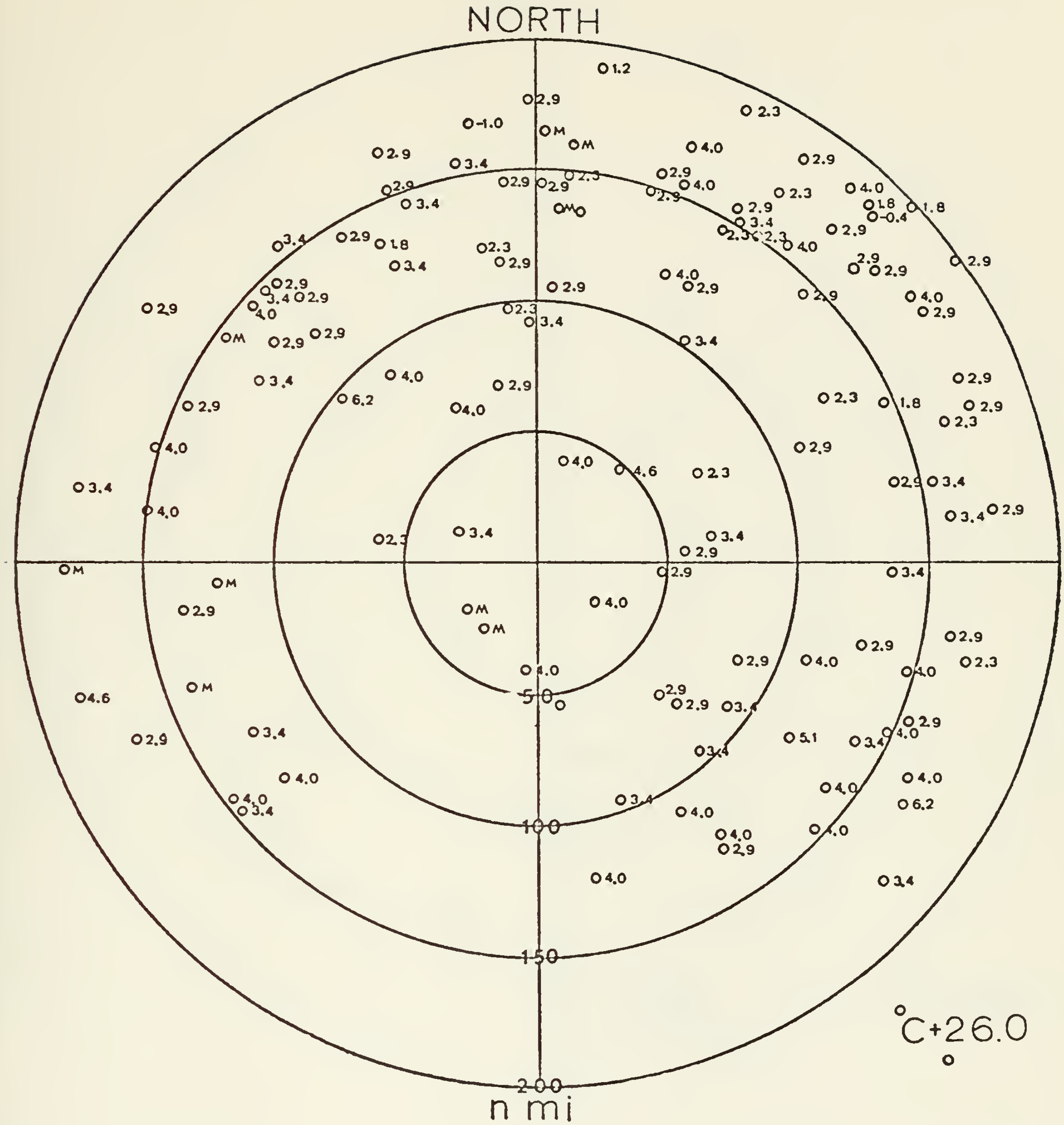

Figure 4. Composite of Observed Sea-Surface Temperatures for Hurricane Hilda--281800GMT SEP - 011800 GMT OCT 1964.

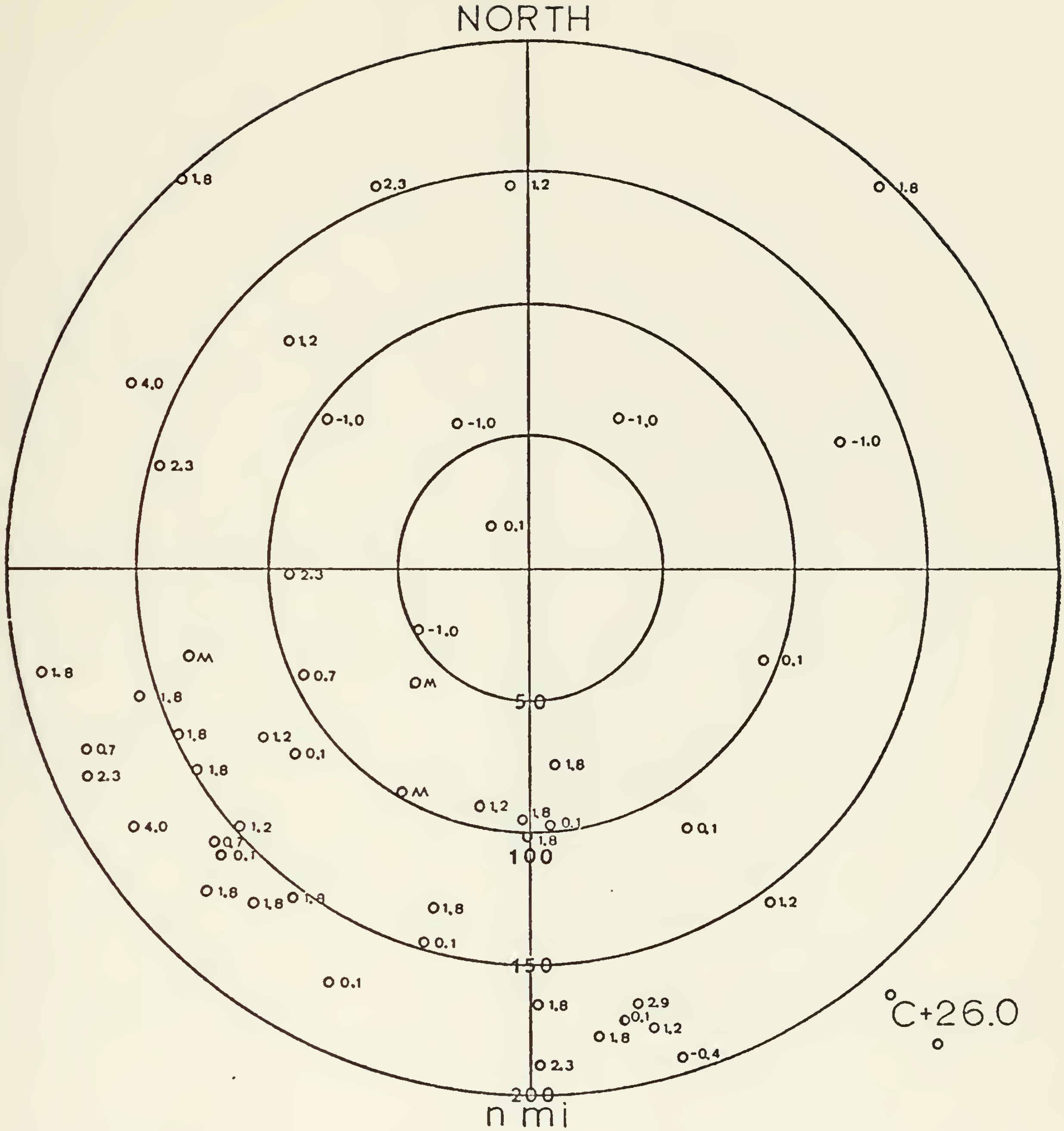

Figure 5. Composite of Observed Air Temperatures for Hurricane Betsy -- 080000GMT SEP - 100000GMT SEP 1965.

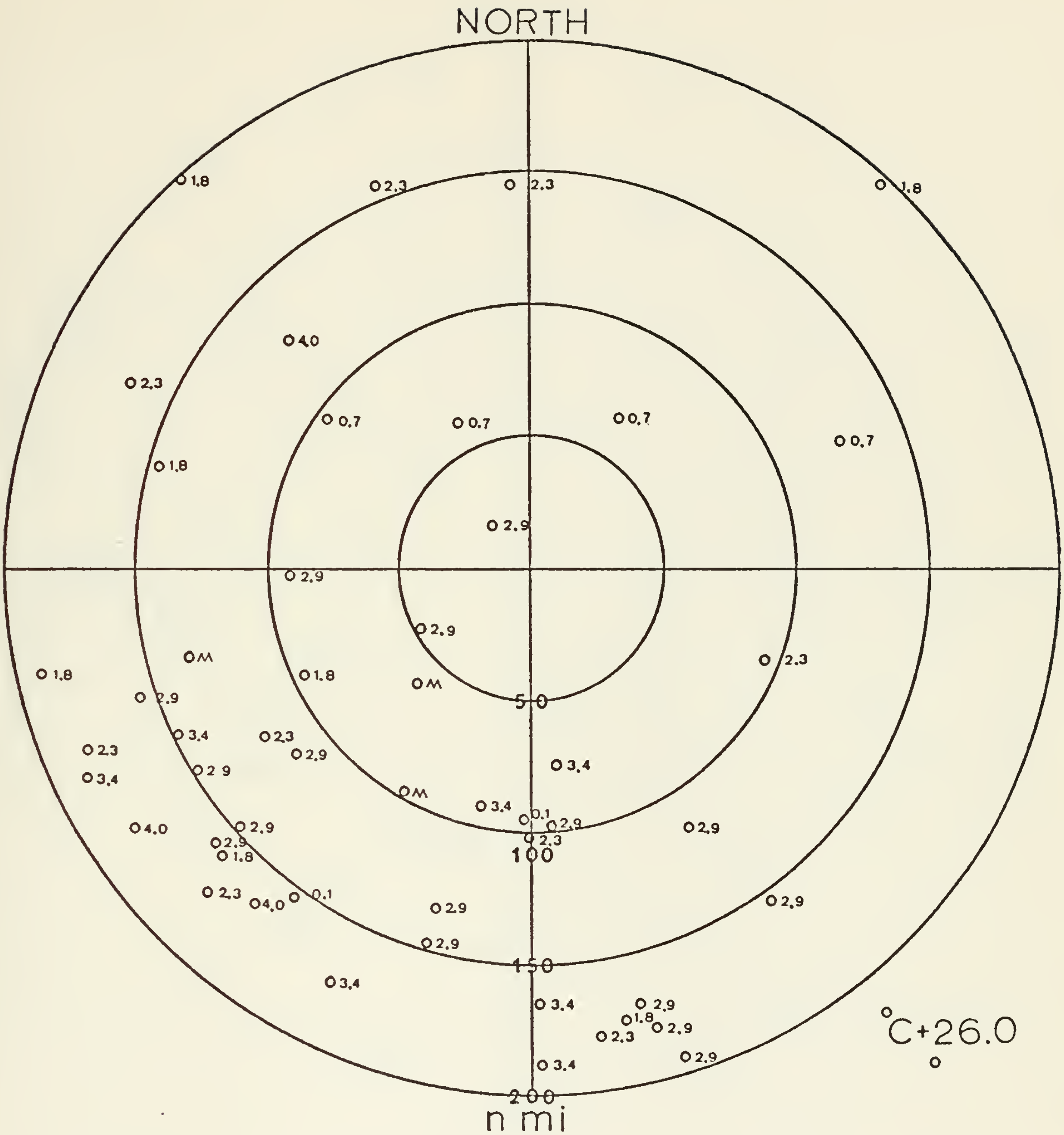

Figure 6. Composite of Observed Sea-Surface Temperatures for Hurricane Betsy--080000GMT SEP - 100000GMT SEP 1965.

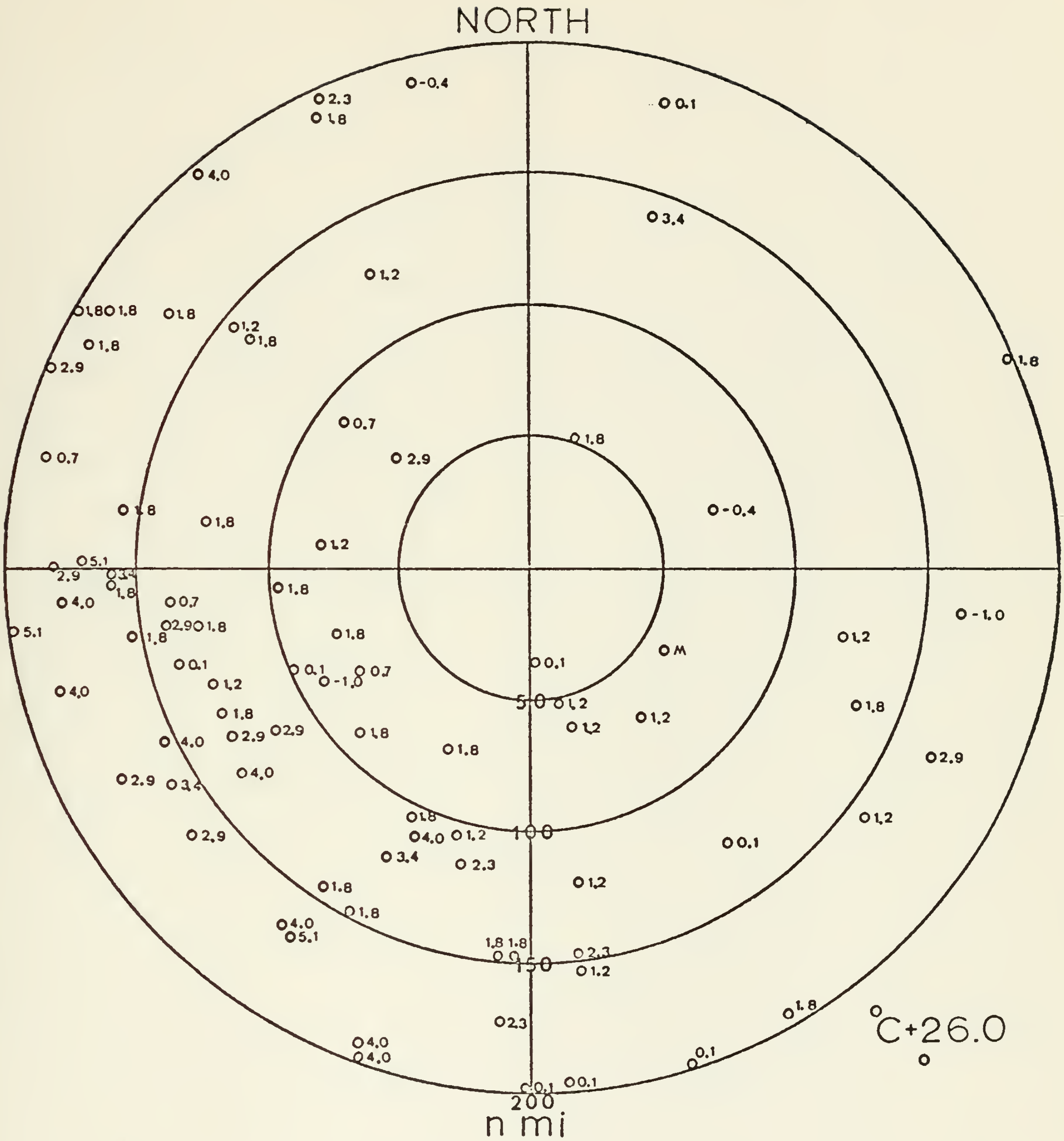

Figure 7. Composite of Observed Air Temperatures for Hurricane Camille--150000GMT AUG - 171800GMT AUG 1969.

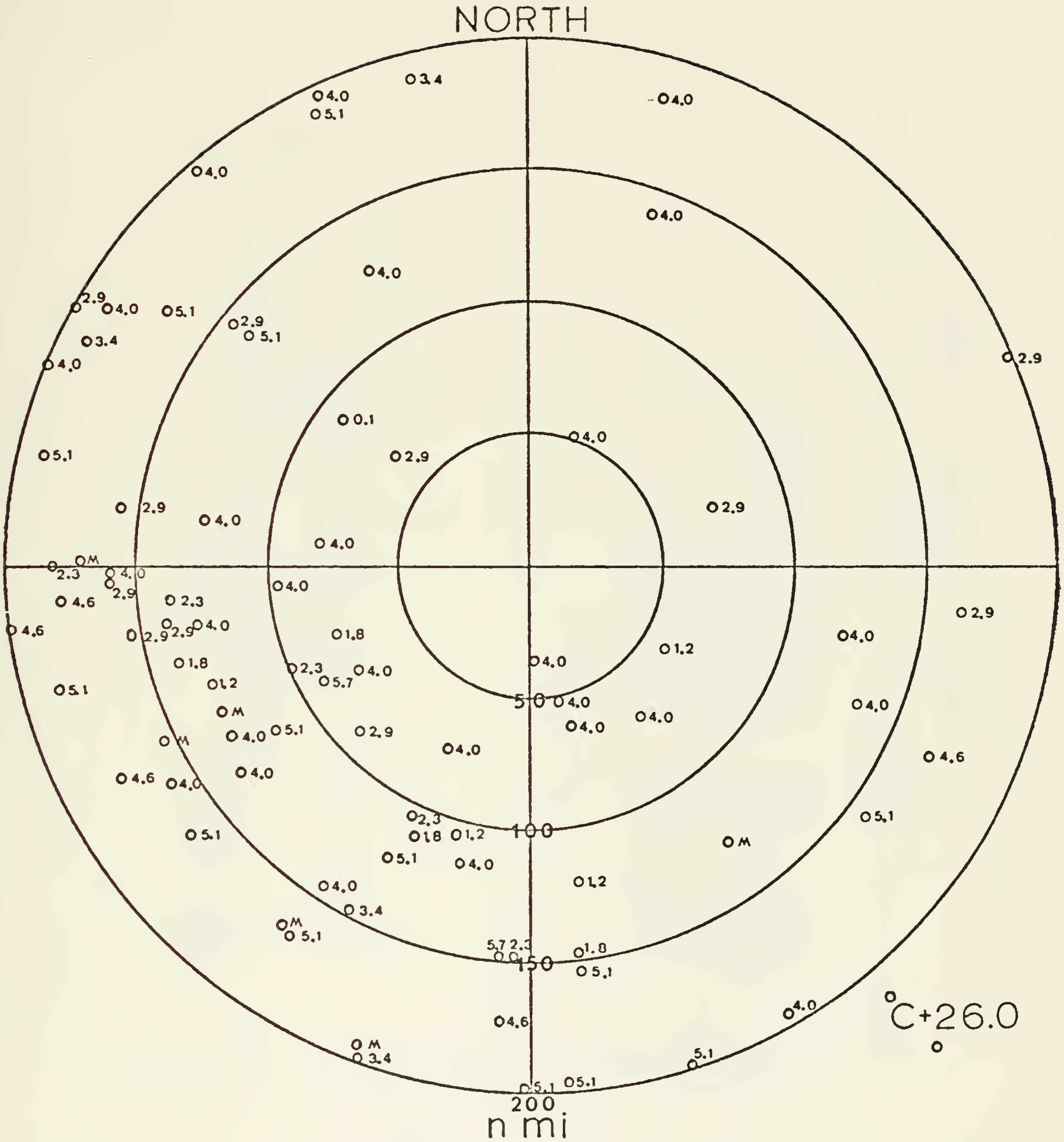

Figure 8. Composite of Observed Sea-Surface Temperatures for Hurricane Camille--150000GMT AUG - 171800GMT AUG 1969.

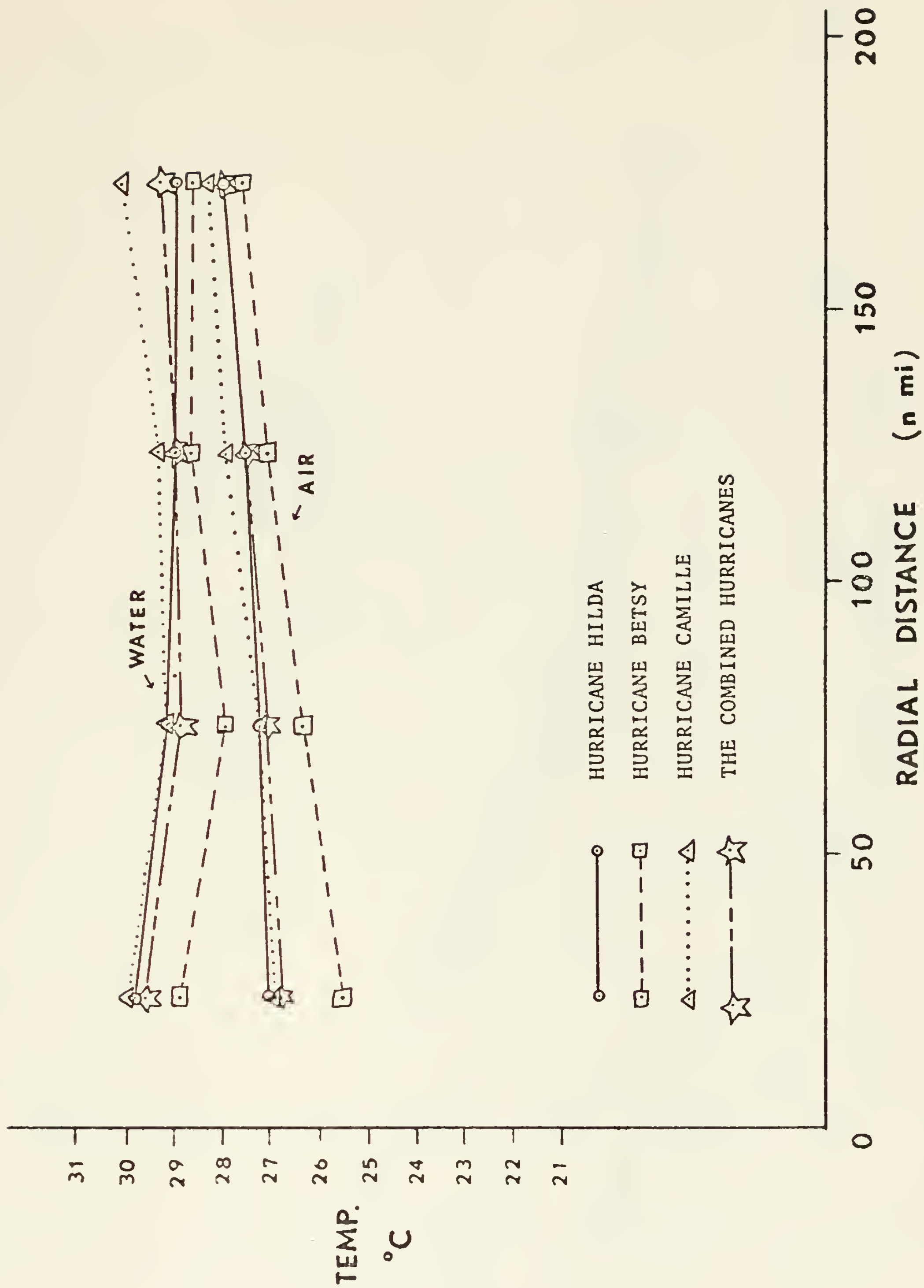

Figure 9. Mean Temperature of Sea-surface and Air vs. Radial Distance from Center for Each Hurricane and Their Combined Values.

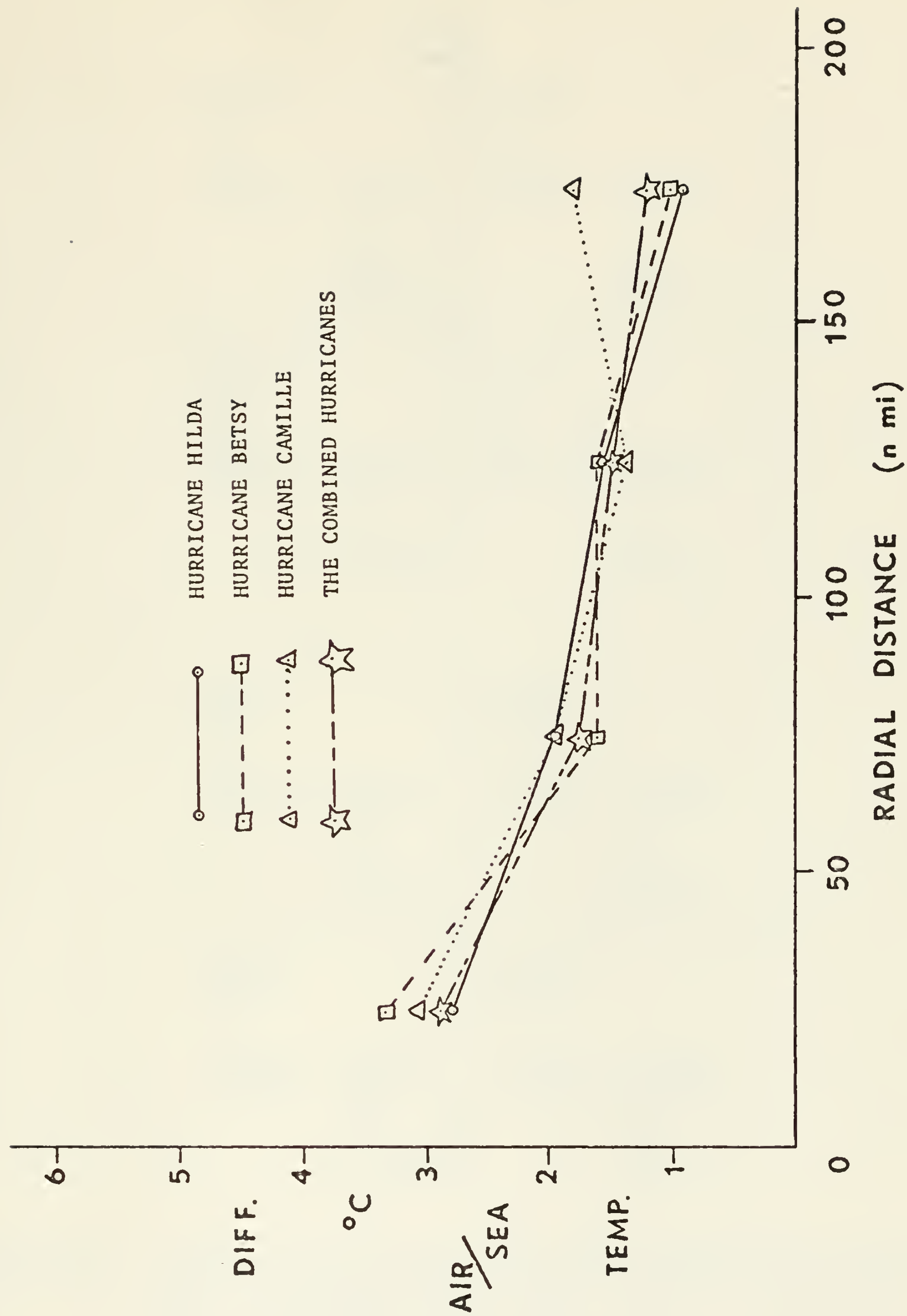

Figure 10. Mean Temperature Differences vs. Radial Distance from Center for Each Hurricane and Their Combined Values.

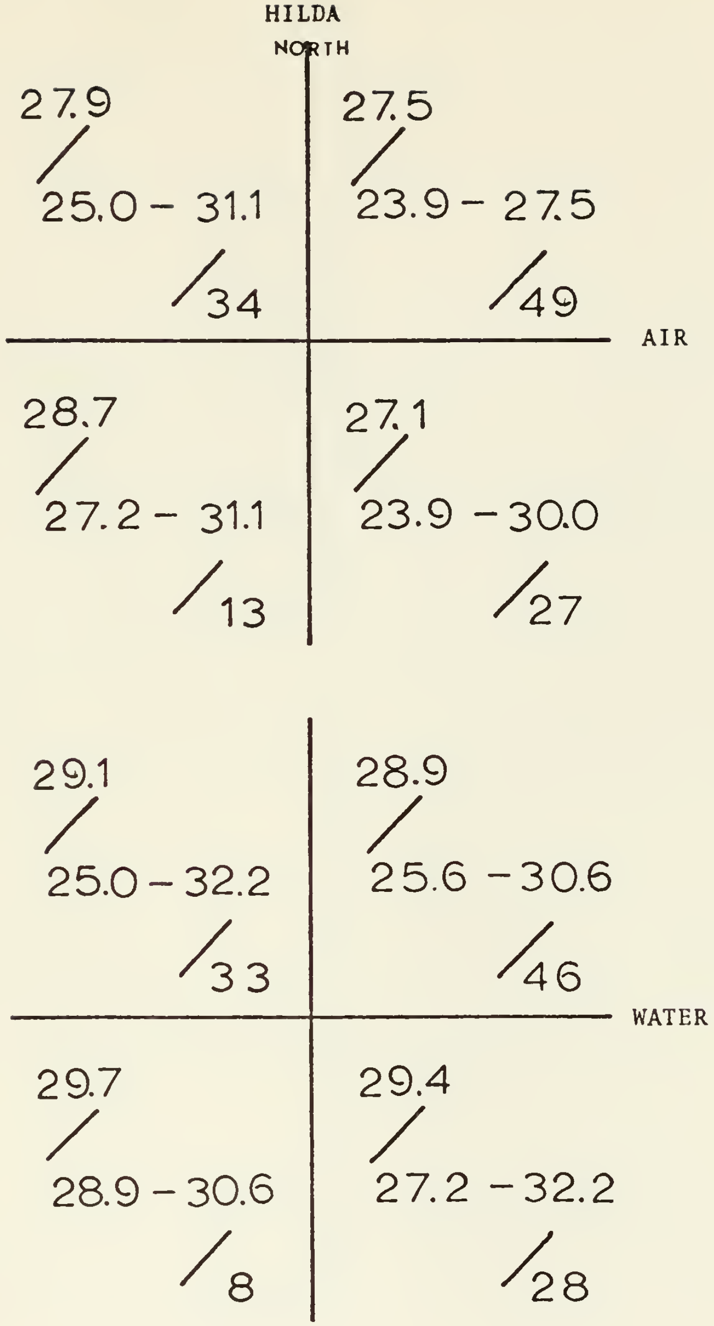

Figure 11. Air and Sea-Surface Observed Temperature Data by Quadrant for Hurricane Hilda -- 281800GMT SEP - 011800GMT OCT 1964. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

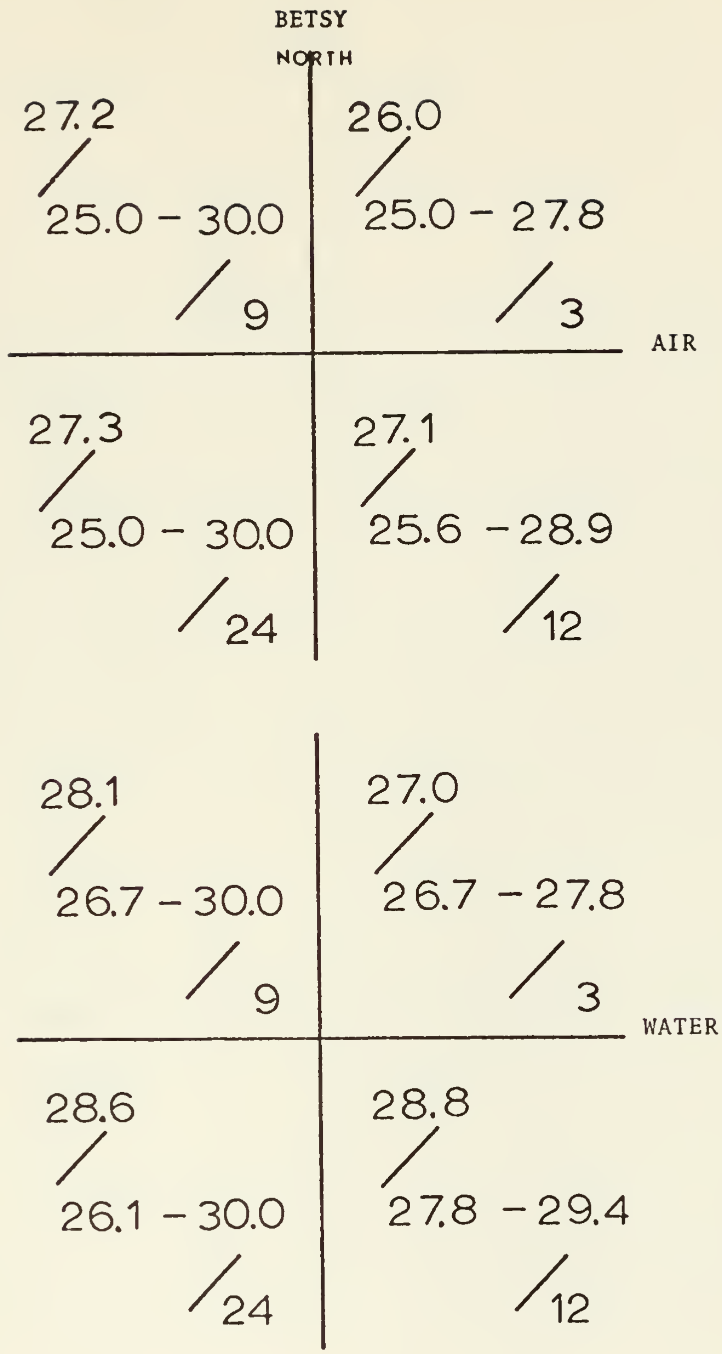

Figure 12. Air and Sea-Surface Observed Temperature Data by Quadrant for Hurricane Betsy -- 080000GMT SEP - 100000GMT SEP 1965. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

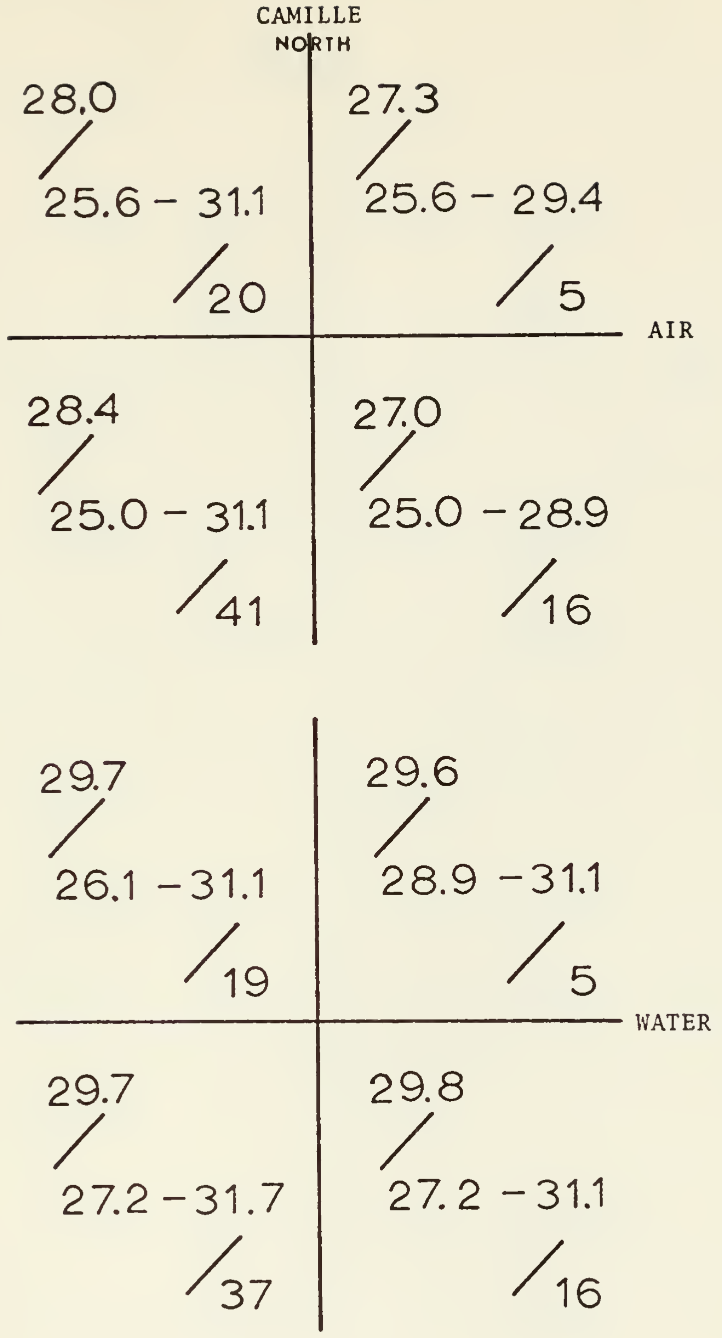

Figure 13. Air and Sea-Surface Observed Temperature Data by Quadrant for Hurricane Camille -- 150000GMT AUG - 171800GMT AUG 1969. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

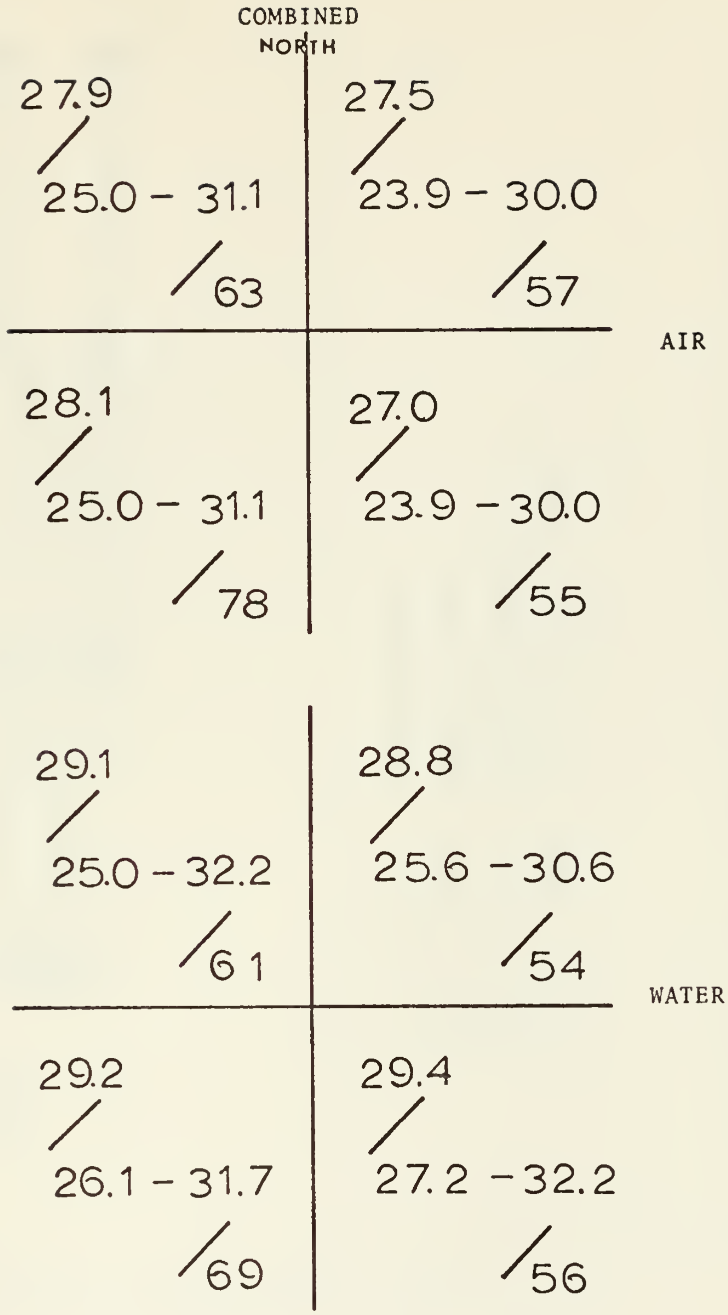

Figure 14. Air and Sea-Surface Observed Temperature Data by Quadrant for the Combined Hurricanes. (MEAN/RANGE OF OBSERVATIONS/NO. OF OBSERVATIONS)

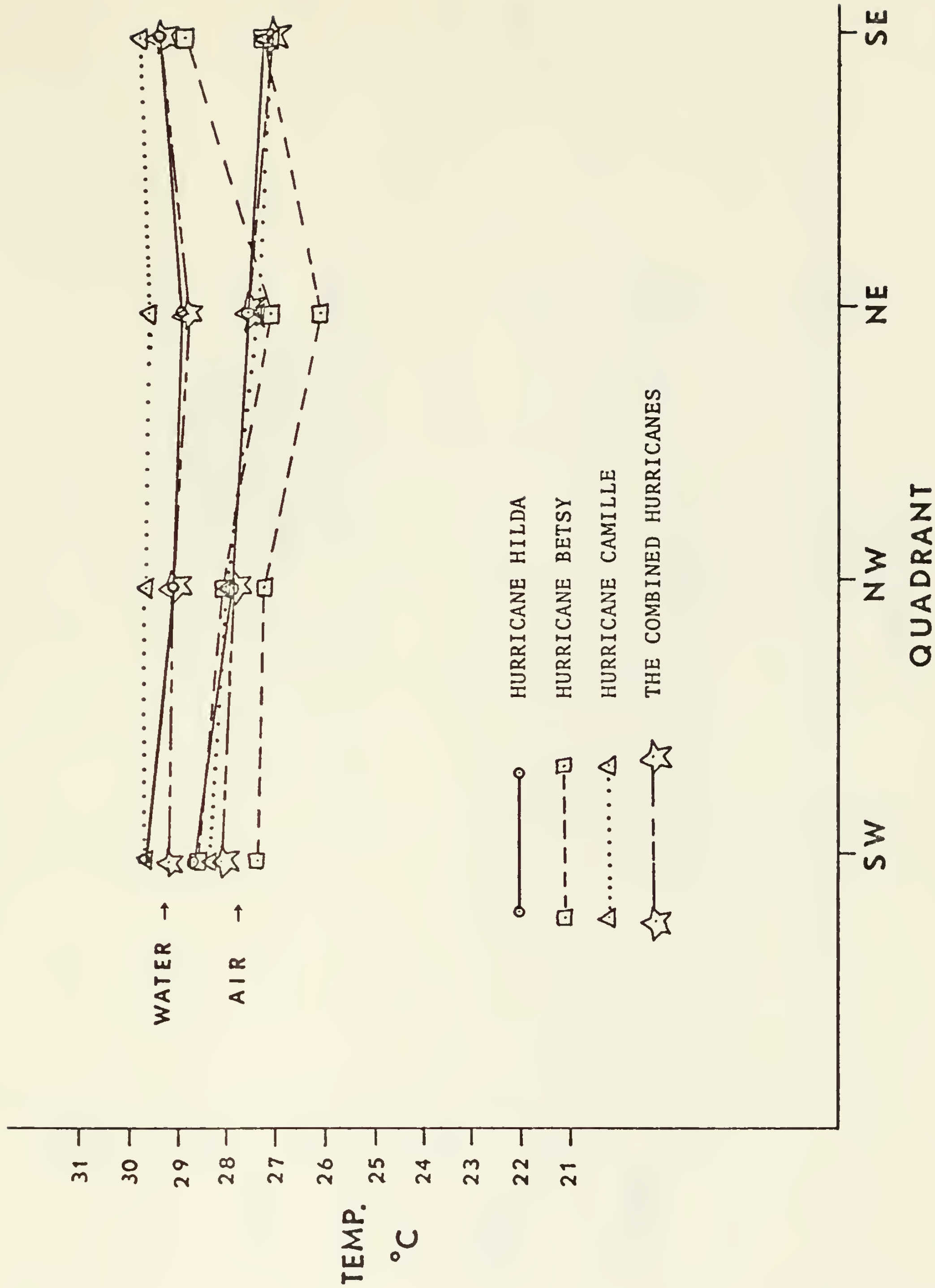

Figure 15. Mean Temperature of Sea-surface and Air vs. Quadrant for Each Hurricane and Their Combined Values.

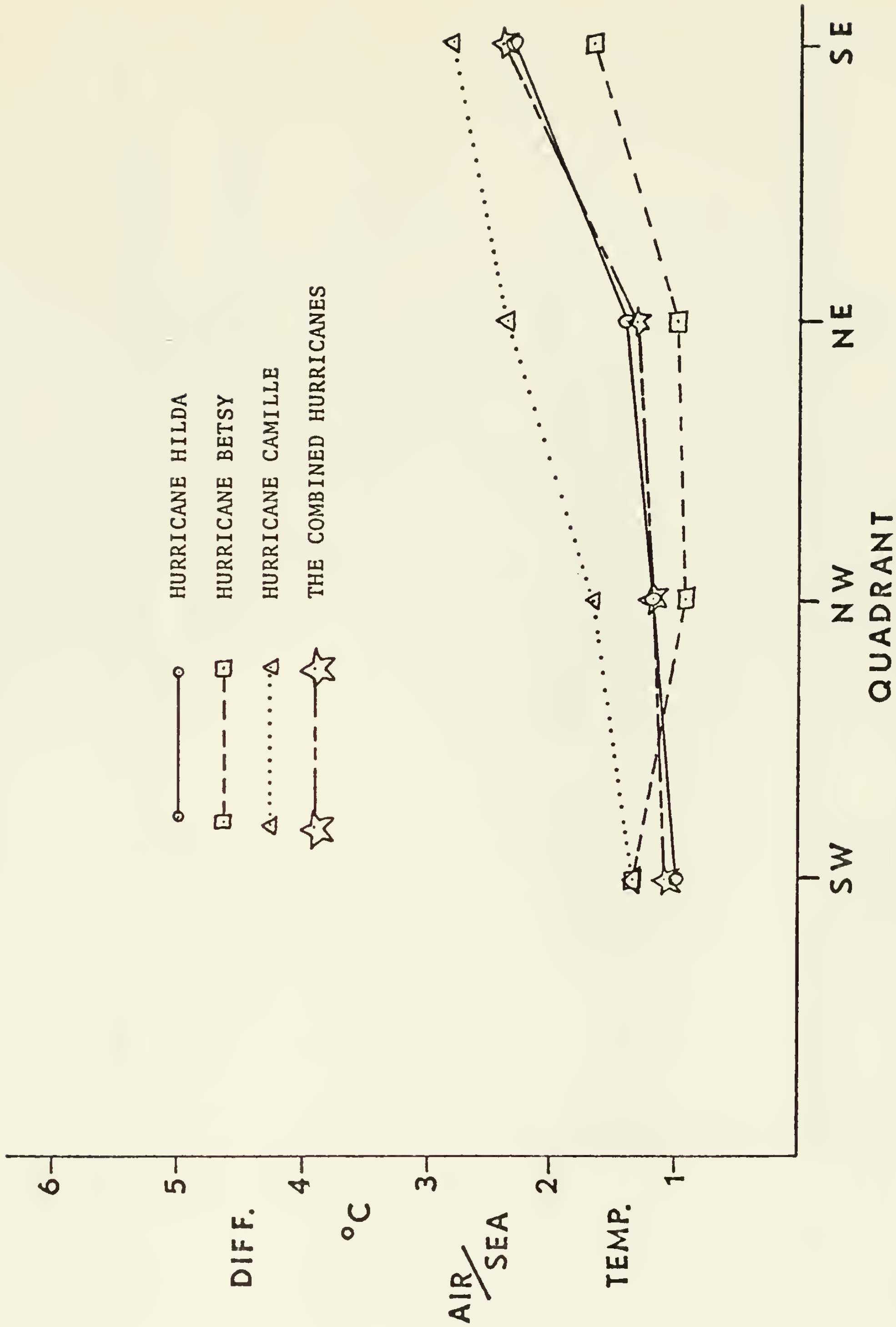

Figure 16. Mean Temperature Differences vs. Quadrant for Each Hurricane and Their Combined Values.

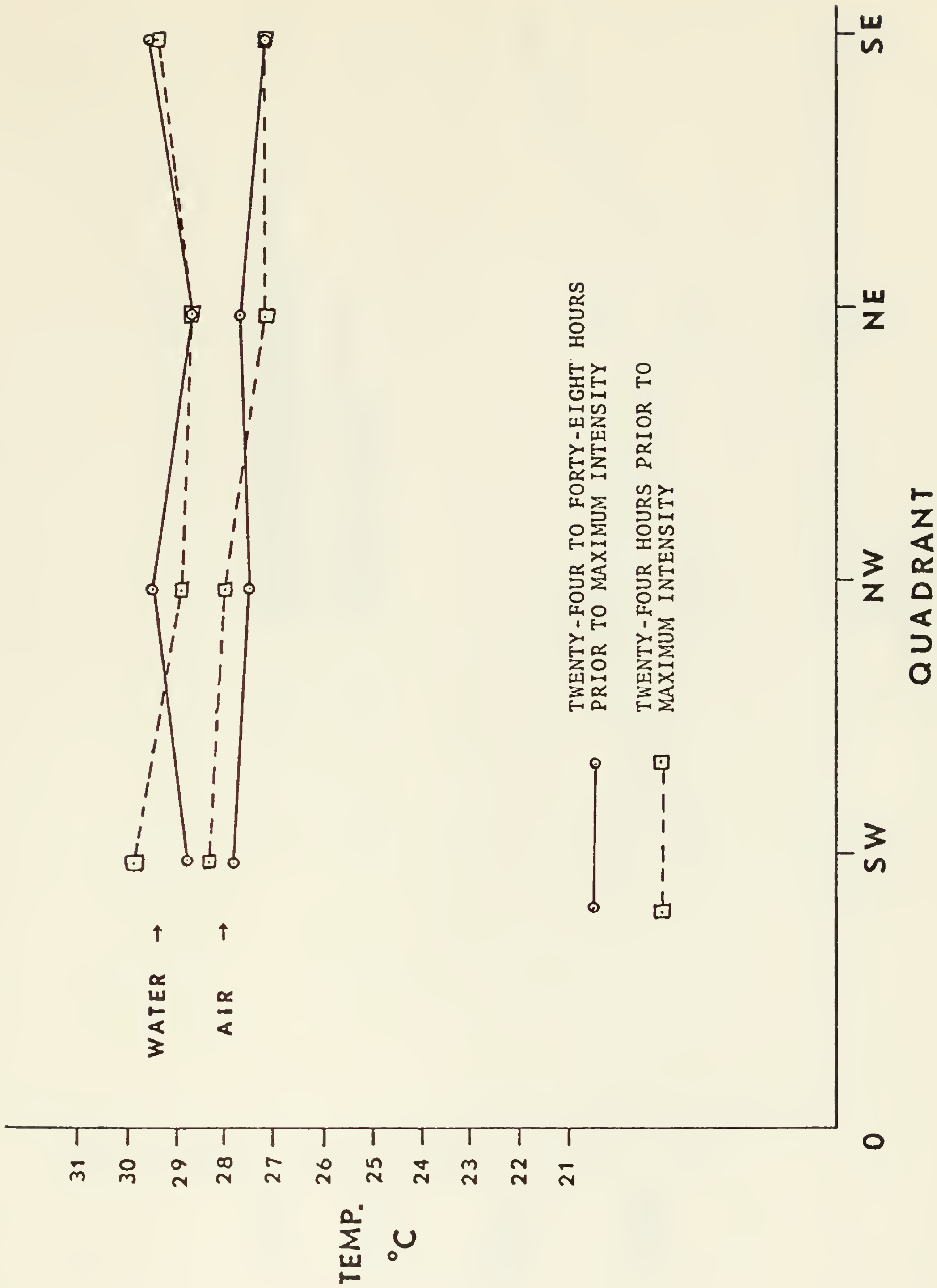

Figure 17. Mean Temperature of Sea-surface and Air vs. Quadrant for the Combined Hurricanes.

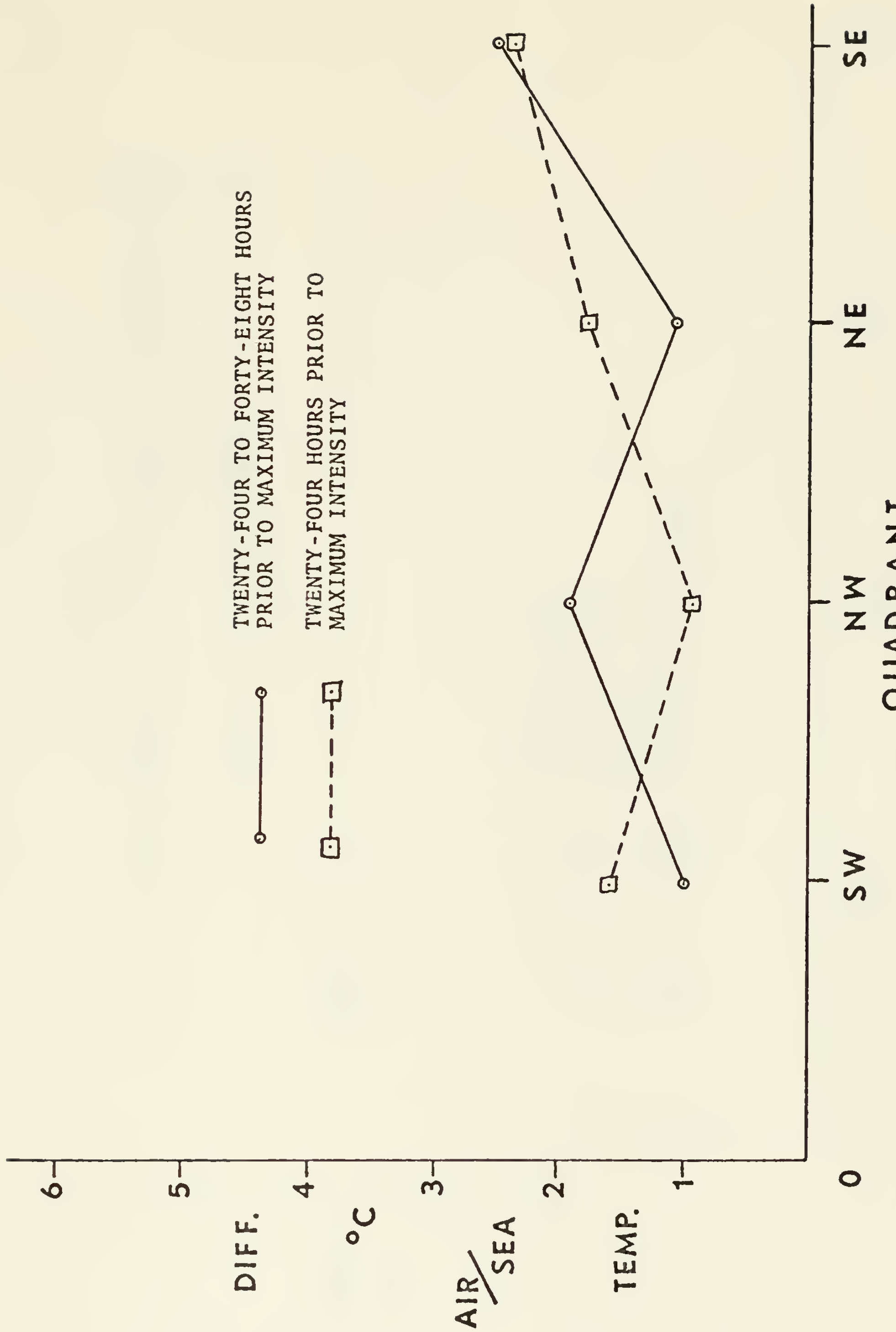

Figure 18. Mean Temperature Differences vs. Quadrant for the Combined Hurricanes.

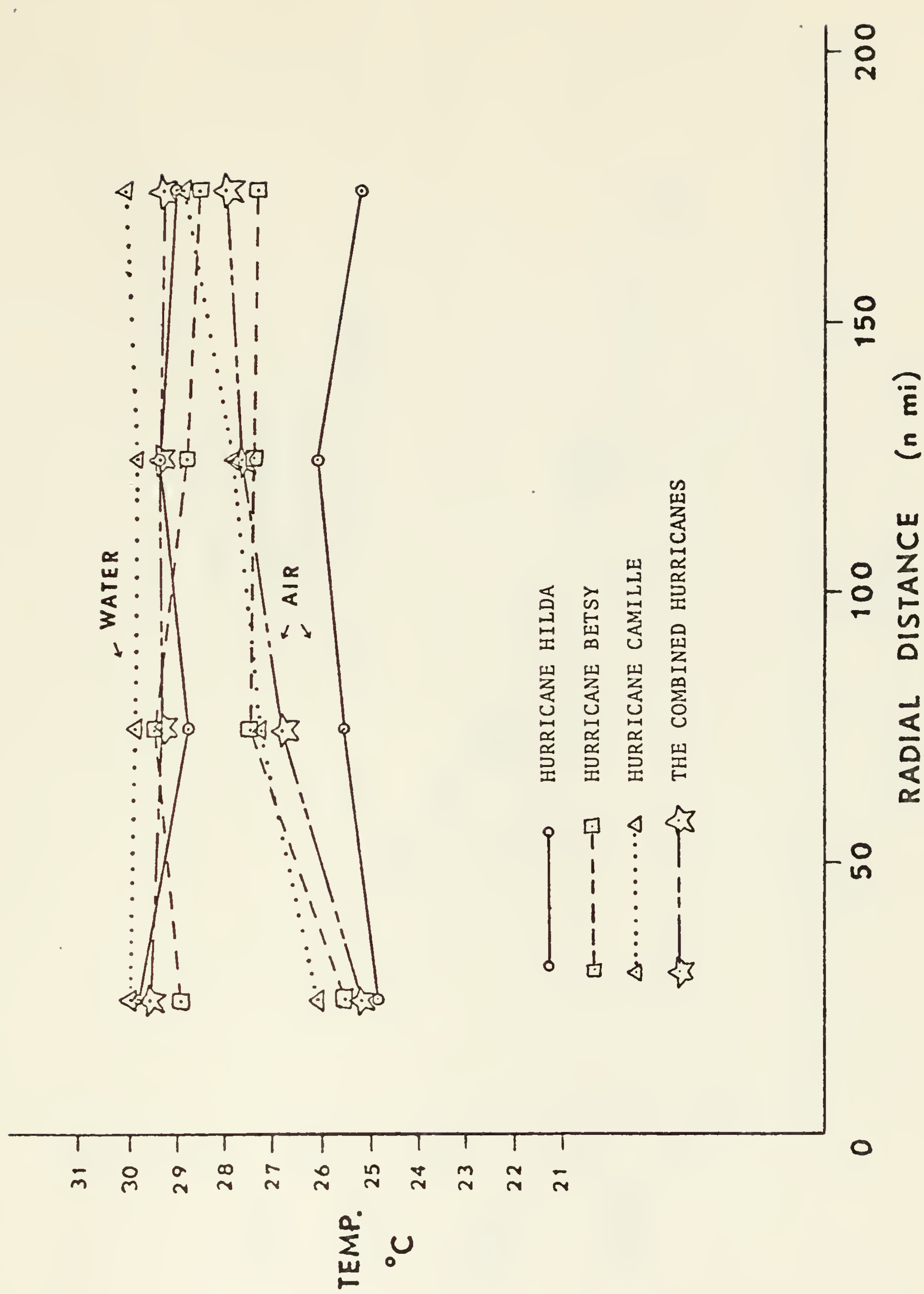

Figure 19. Mean Temperature of Sea-surface and Air vs. Radial Distance from Center for Each Hurricane and Their Combined Values for the Period of Time 24 Hours Prior to Maximum Intensification.

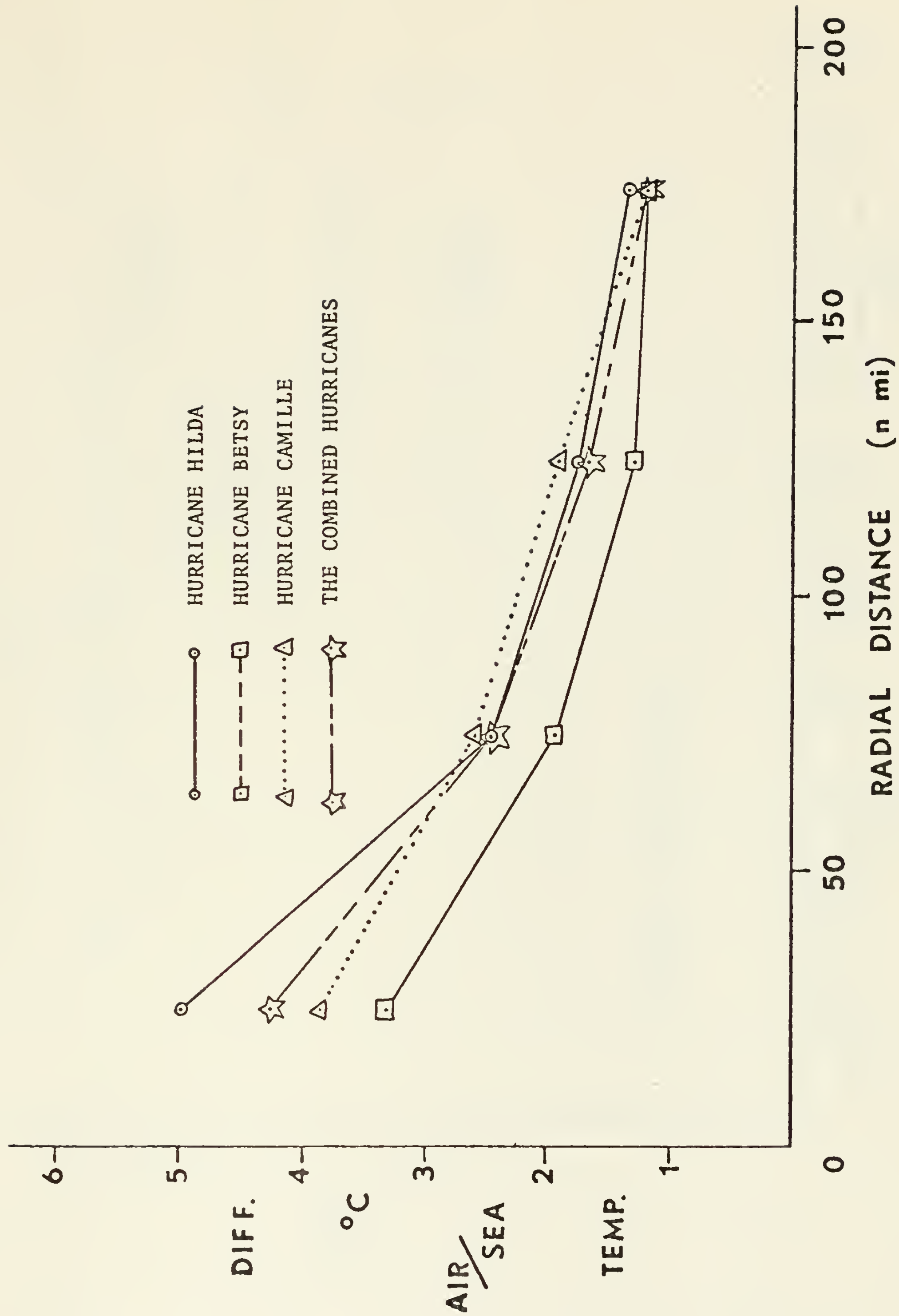

Figure 20. Mean Temperature Differences vs. Radial Distance from Center for Each Hurricane and Their Combined Values for the Period of Time 24 Hours Prior to Maximum Intensification.

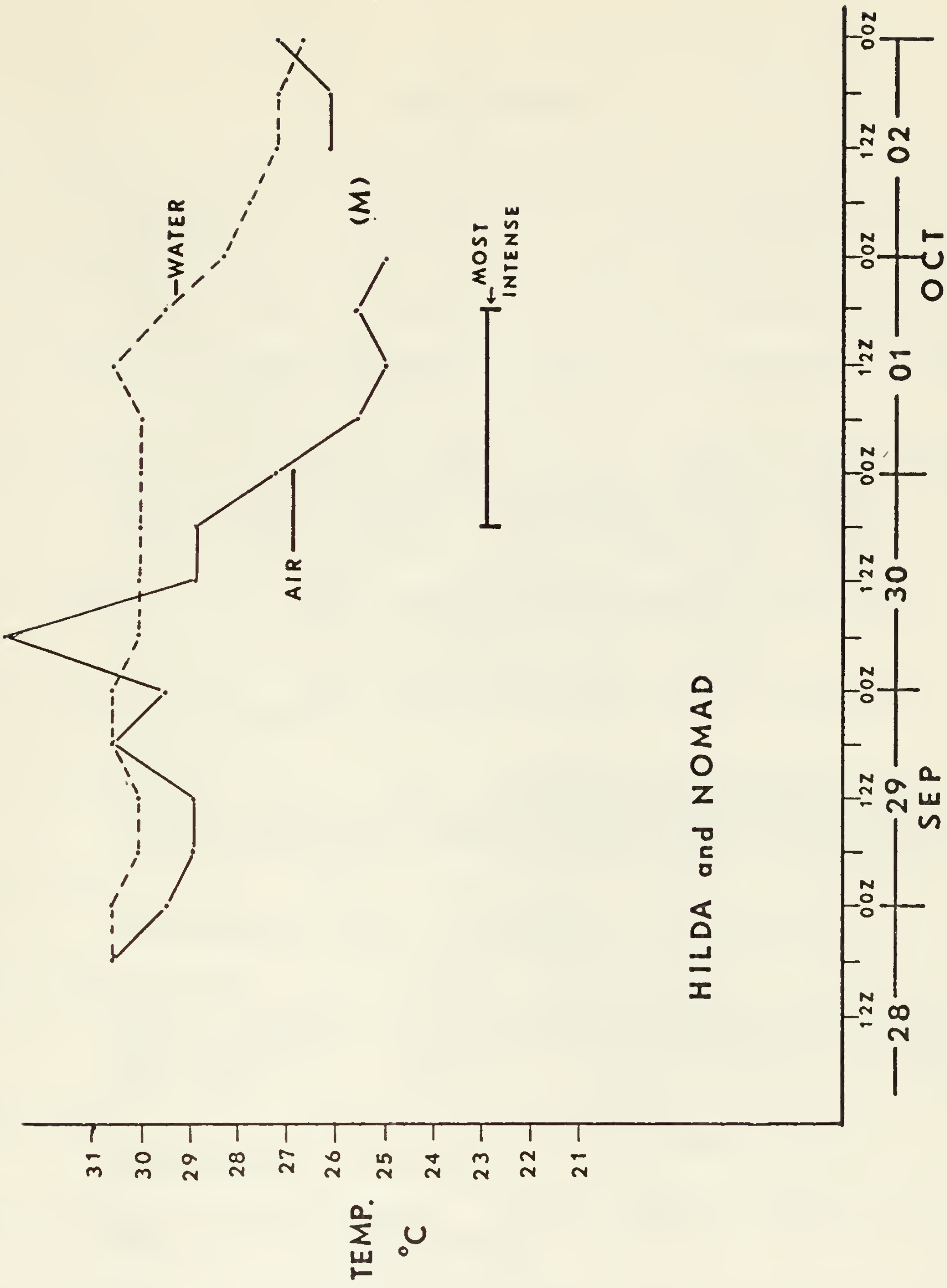

Figure 21. Water and Air Temperature vs. Time for Gulf of Mexico NOMAD during Passage of Hurricane Hilda.

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13. ABSTRACT

Observed near-surface air and sea-surface temperatures for three hurricanes -- Hilda (1964), Betsy (1965) and Camille (1969) -- were studied. Composites were made for each of the storms. These composites were oriented to true north, had diameters of 400 n mi and covered the period in the Gulf of Mexico prior to the time the hurricanes reached maximum intensity. The mean air temperature was less than the mean sea-surface temperature, and this difference varied from 1.2C in the outer region of the composites to 2.9C near the center. In the 24-hour period prior to maximum hurricane intensity, the difference was 4.3C near the center. The data also indicated that the distribution of air-sea temperature difference within the hurricanes varied by quadrant with the southeast quadrant containing the largest over-all average difference (2.4C) and the southwest quadrant averaging 1.1C.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
1. Air-sea interaction						
2. Hurricane						
3. Near-surface air temperature						
4. Sea-surface temperature						

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